Tokamaks and tokamak-reactors with Li Walls

Leonid E. Zakharov,

Princeton University, Princeton Plasma Physics Laboratory

Prepared for the Tore Supra Seminar

February 11, 2002, Cadarache, France

[1] **This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.**

Abstract

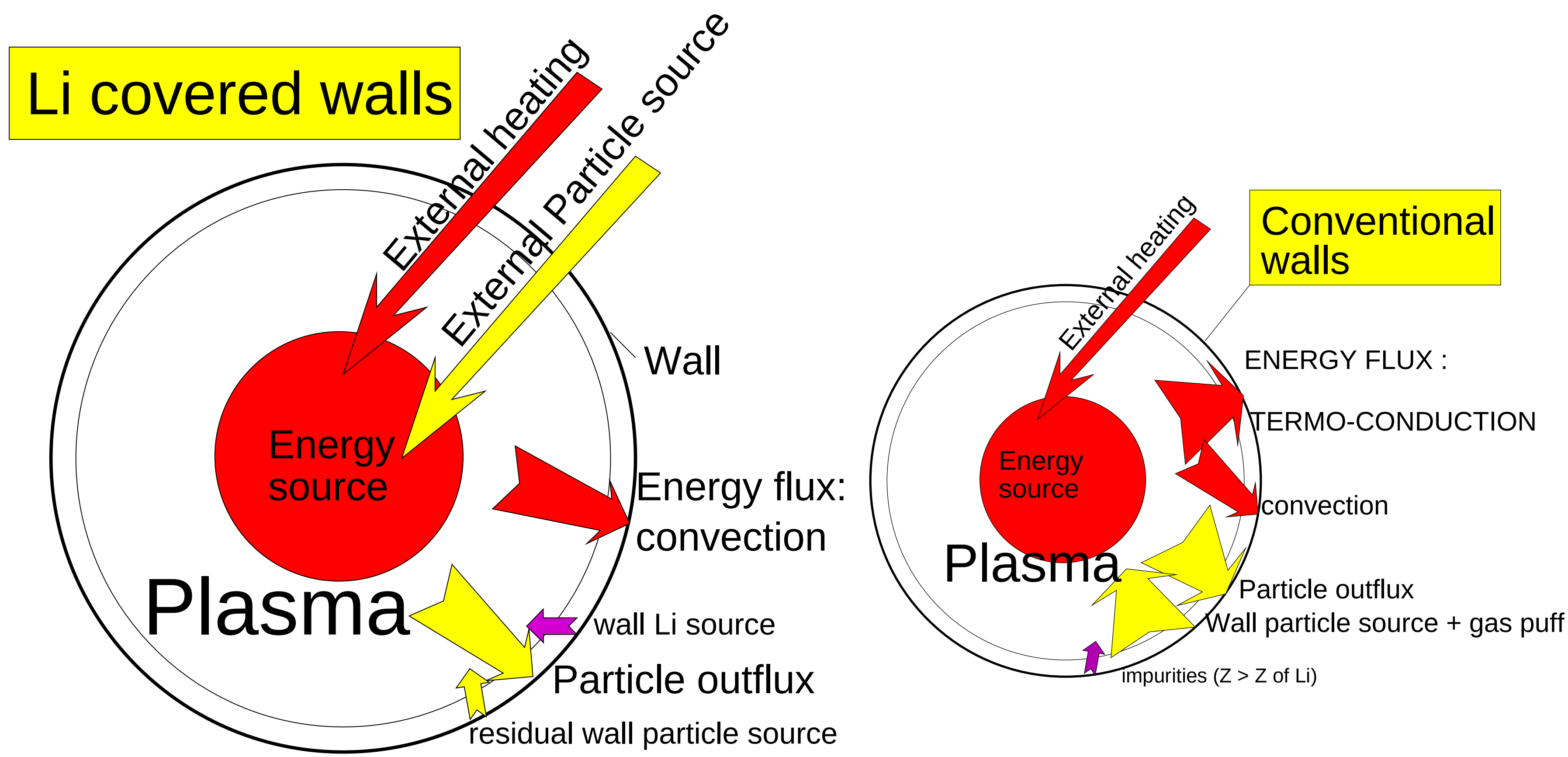
Lithium covered walls, conformal to the plasma surface, represent a new, "LiWall", concept for solving the problem of the "first wall" for both the next step tokamaks and the tokamak reactors. From the technical point of view, this concept relies on distribution of the power and particle flux over the large wall surface, thus, dramatically enhancing total power and particle extraction capabilities of the machines. In terms of the plasma physics, LiWalls may utilized a new, low recycling regimes with the high temperature pedestal at the plasma edge, flattened temperature profiles, suppressed thermo-conduction and enhanced stability (due to flattened q-profiles and presence of the conducting wall at the plasma boundary). At the research stage, such a confinement regime may be studied on tokamaks with the (solid) lithium coated copper shells (with a special interface layer). For the tokamak reactors, LiWalls lead to a new, "Yacht sail" design approach with a dynamically balanced first wall, intense plasma facing (liquid) lithium streams and the FLiBe neutron energy absorbing blanket layer. If developed, this design would significantly reduce the amount of activated structural elements in the neutron zone and make acceptable a pulsed tokamak reactor regime.

Supporting material for the talk can be found on the web-page http://w3.pppl.gov/~zakharov

OUTLINE

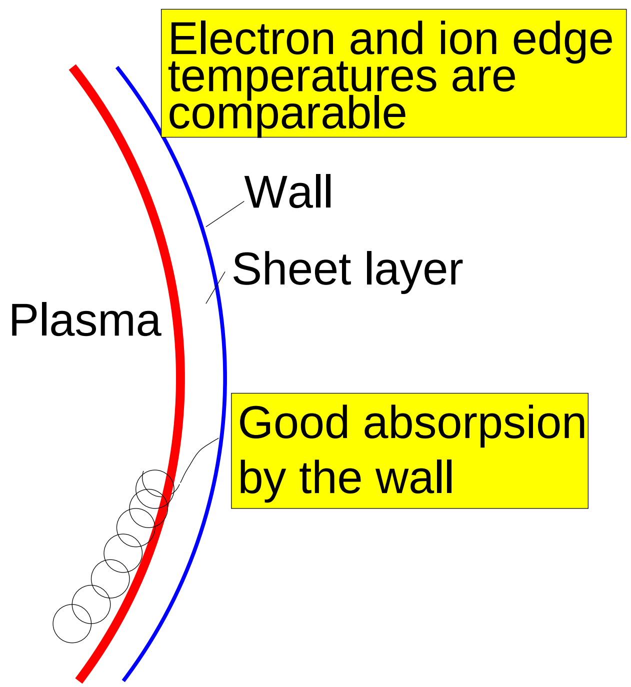
1. Introduction.
2. Basic properties of lithium.
   (a) Gettering plasma particles by lithium.
   (b) Power extraction capabilities of LiWalls.
3. Confinement and stability in low recycling regime.
4. MHD of liquid lithium.
   (a) Basic Reynolds numbers.
   (b) Magnetic propulsion of Intense Lithium Streams.
   (c) Stabilization by Intense Li streams.
5. Yacht Sail approach for tokamak-reactors.
   (a) Dynamic balancing.
   (b) FLiBe blanket.
   (c) Fabric-like vacuum chamber.
6. Summary.
7. *Frequently asked questions.*

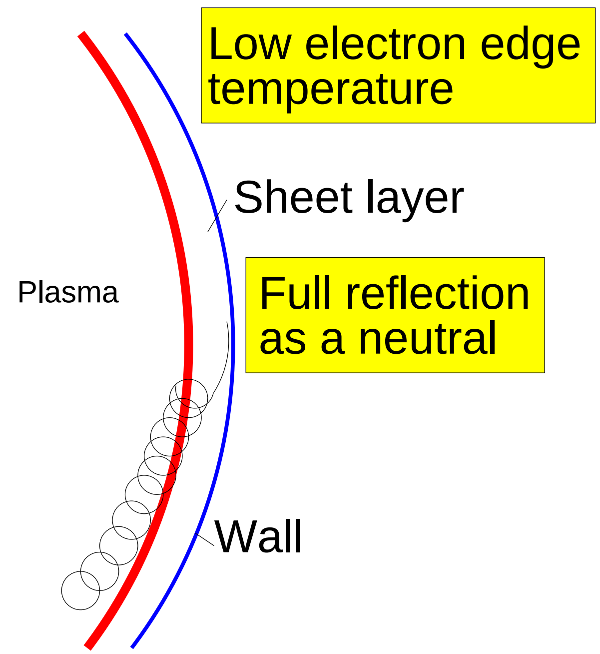
Li is an excellent getter for the hydrogen plasma particles.



Lithium can be propelled along the walls
for power and particle extraction.

The concept of LiWalls relies on lithium covered walls conformal to the plasma (no divertor)





Sheet potential near the walls is determined by the electron energy, $E \simeq 3T_e/\rho_i$.

- Physics goal

$$n \cdot T \cdot \tau_E > 50\ [10^{20} m^{-3} \cdot \text{keV} \cdot \text{sec}] \tag{1.1}$$

or

$$\beta \cdot B^2 \cdot \tau_E > 4, \quad \beta = 0.08 \frac{n \cdot T}{B^2}. \tag{1.2}$$

At present, one lane road, toward increase in τ_E. Not a reactor way.

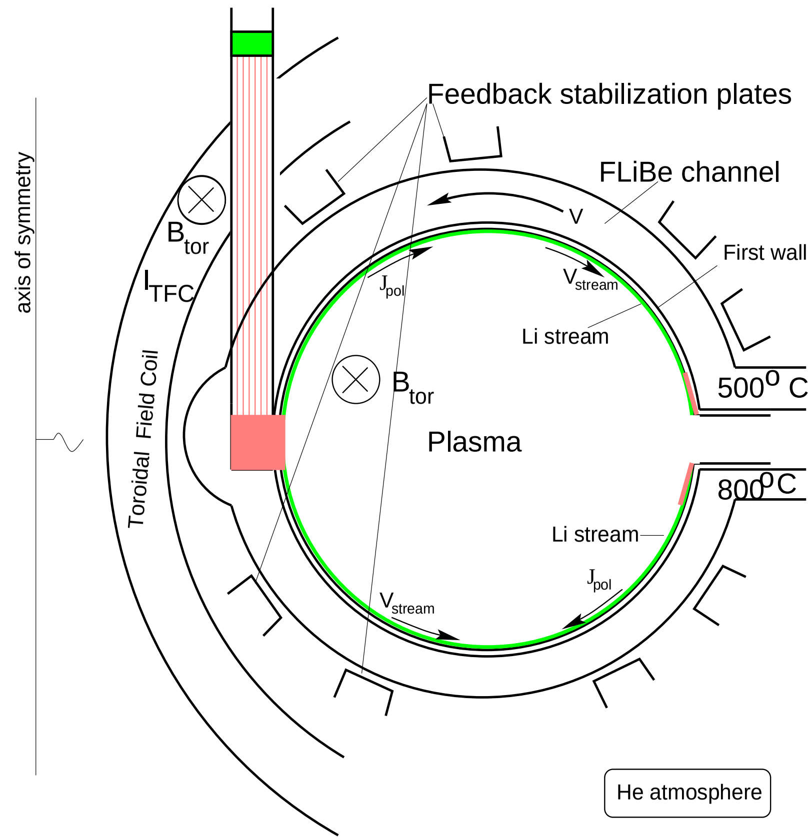
$$P_{fusion} = 5 \frac{E_{plasma}}{\tau_E}. \tag{1.3}$$

LiWalls put a conducting wall right at the plasma edge and open a road to fusion reactor with $\beta > 10\%$.

- Confinement: peaked temperature, sawtooth oscillations, Troyon limit, turbulent transport, necessity in controlling profiles.

  LiWalls rely on the low recycling regime, high edge temperature, flattened temperature, suppression (elimination) of the turbulent transport.

LiWalls make external plasma MHD control compatible with the fusion reactor:



- "passive" conducting shell right at the plasma boundary;
- protection of feedback stabilization plates from 14 MeV neutrons;
- accessibility to feedback stabilization plates;
- no-conducting structures between feedback plates and conducting shell;
- additional stabilization by the lithium streams (for free);

- Divertor limits the power extraction by concentrating power deposition (average wall load in ITER < 1MW/m^2).

  Capacities of LiWalls (with distributed pwoer deposition) exceed reactor requirements ($\simeq$ 15 MW/m^2).

- Neutron flux deteriorates mechanical properties of the high-Z plasma facing components and blanket structure. It produces a long lasting activation.

  In LiWalls the first wall consists of fast plasma facing lithium streams and liquid FLiBe blanket (not damagable and non activatable).

  "Yacht sail" design approach minimizes use of high-Z structural components.

2 Basic properties of lithium

Lithium:

1.*	Atomic mass	6.941	
2.*	Mass density at 600	0.495 $\frac{g}{cm^3}$	half of water
3.*	Melting temperature	180.54 C^o	
4.*	Boiling temperature	1347 C^o	
5.**	Conductivity σ at 600^o K	3.4·10^6 $\frac{1}{\Omega \cdot m}$	1/17.5 of copper
6.*	Heat capacity c_p at 600^o K	4253 $\frac{J}{kg \cdot K}$	like water
7.**	Thermal cond. k_T at 600^o K	47.6 $\frac{W}{m \cdot K}$	1 $\frac{MW}{m^2}$ at T'=210$^o/cm$
8.*	Melting heat Q_{melt}	0.432 kJ/g	30 % $>$ than water
9.**	Viscosity ν at 600^o K	0.42·10^{-3} $Pa \cdot s$	like water
10.*	Surface tension at 600^o K	0.339$\frac{N}{m}$	

[*] "Handbook of Physical Quantities", Ed. by Igor S.Grigoriev and Evgenii Z. Melnikov, Russian Research Center "Kurchatov Institute", Moscow, Russia. CRC press, Boca Raton, New York, London, Tokio (ISBN 0-8493-2861-6)

[**] "Handbook of Thermodynamic and Transport Properties of Alkali Metals", Editor Roland W. Ohse, Blackwell Scientific Publications, Oxford, London, Edinburgh, Boston, Palo Alto, Melbourne (ISBN 0-632-01447-4).

Derived properties of Lithium:

1. Volume density n_{Li}	$46.33 \cdot 10^{21}\ \frac{1}{cm^3}$
2. Surface density $\frac{dN_{Li}}{dS}$	$1.29 \cdot 10^{19}\ \frac{1}{m^2}$
3. Line density $\frac{dN_{Li}}{dh}$	$3.59 \cdot 10^{7}\ \frac{1}{cm}$
4. Thickness of a monolayer	$2.78 \cdot 10^{-8}\ cm$

For a tokamak with the circular cross-section the number of plasma particles compared to the number of Li atoms on the wall surface

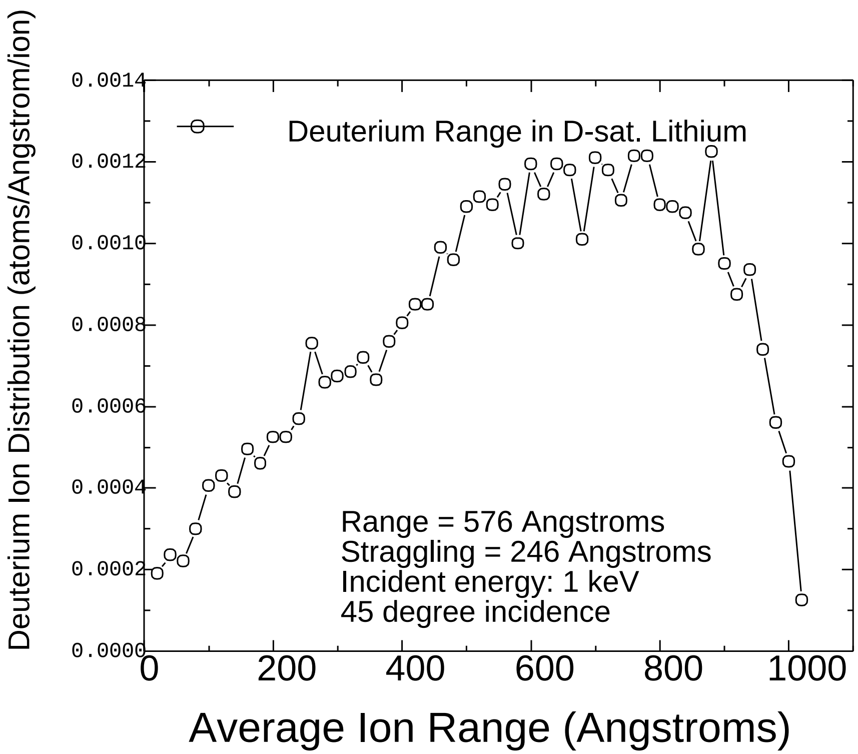
$$V = 2\pi R \pi a^2, \quad S_{wall} = 2\pi R 2\pi a, \quad N_{plasma} = \langle n_e \rangle V, \qquad (2.1)$$
$$N_{Li} = \frac{dN_{Li}}{dS} S$$

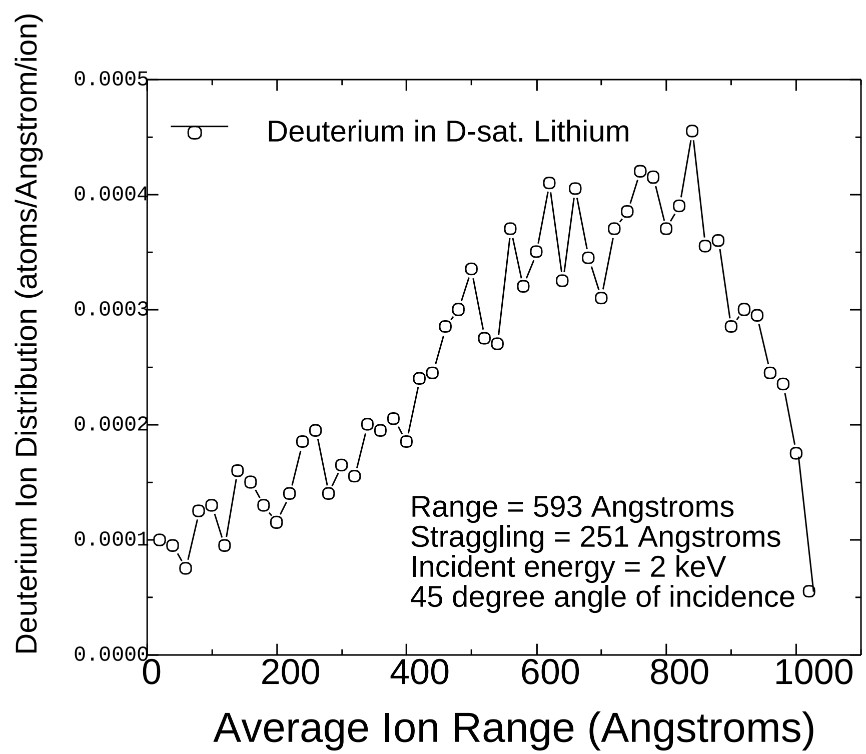
can be calculated as

$$N_{monolayers} \equiv \frac{N_{plasma}}{N_{Li}} = \frac{\langle n_e \rangle}{2\frac{dN_{Li}}{dS}} a = 3.87 a_{[m]} \langle n_e \rangle_{[10^{20}]} . \qquad (2.2)$$

Averaged Ion Range Of Deuterium incident on D-sat. Lithium

(TRIM calculations with 10000 flights by J.P.Allain, University of Illinoice, April, 2000)

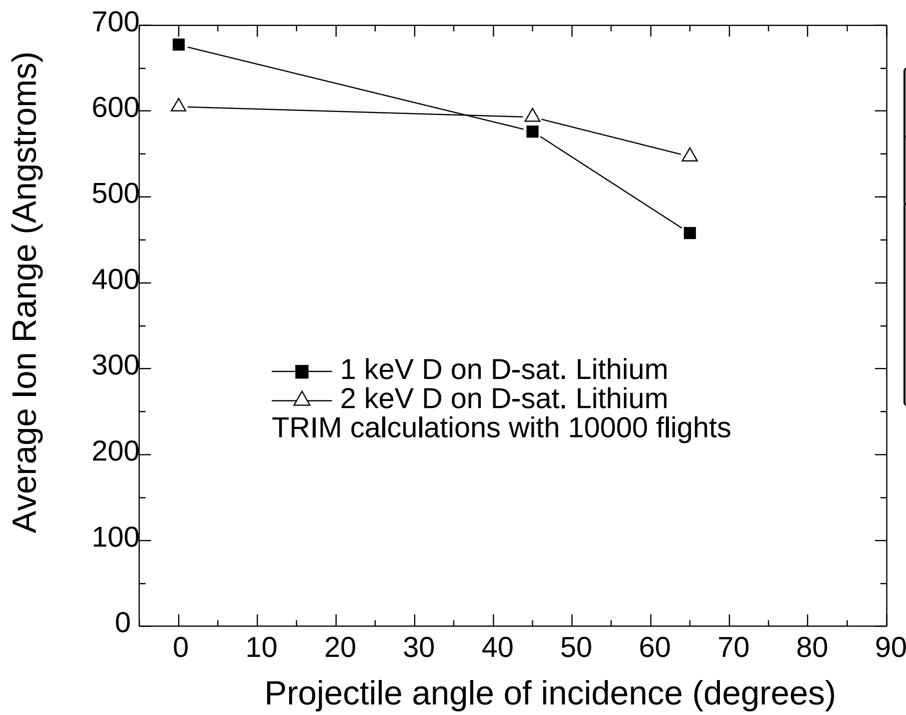




1 keV D on D-sat Li, Average Ion Range = 576 A
2 keV D on D-sat Li, Average Ion Range = 593 A

Averaged Ion Range as a function of projectile angle of incidence

(TRIM calculations with 10000 flights by J.P.Allain, University of Illinoice, April, 2000)

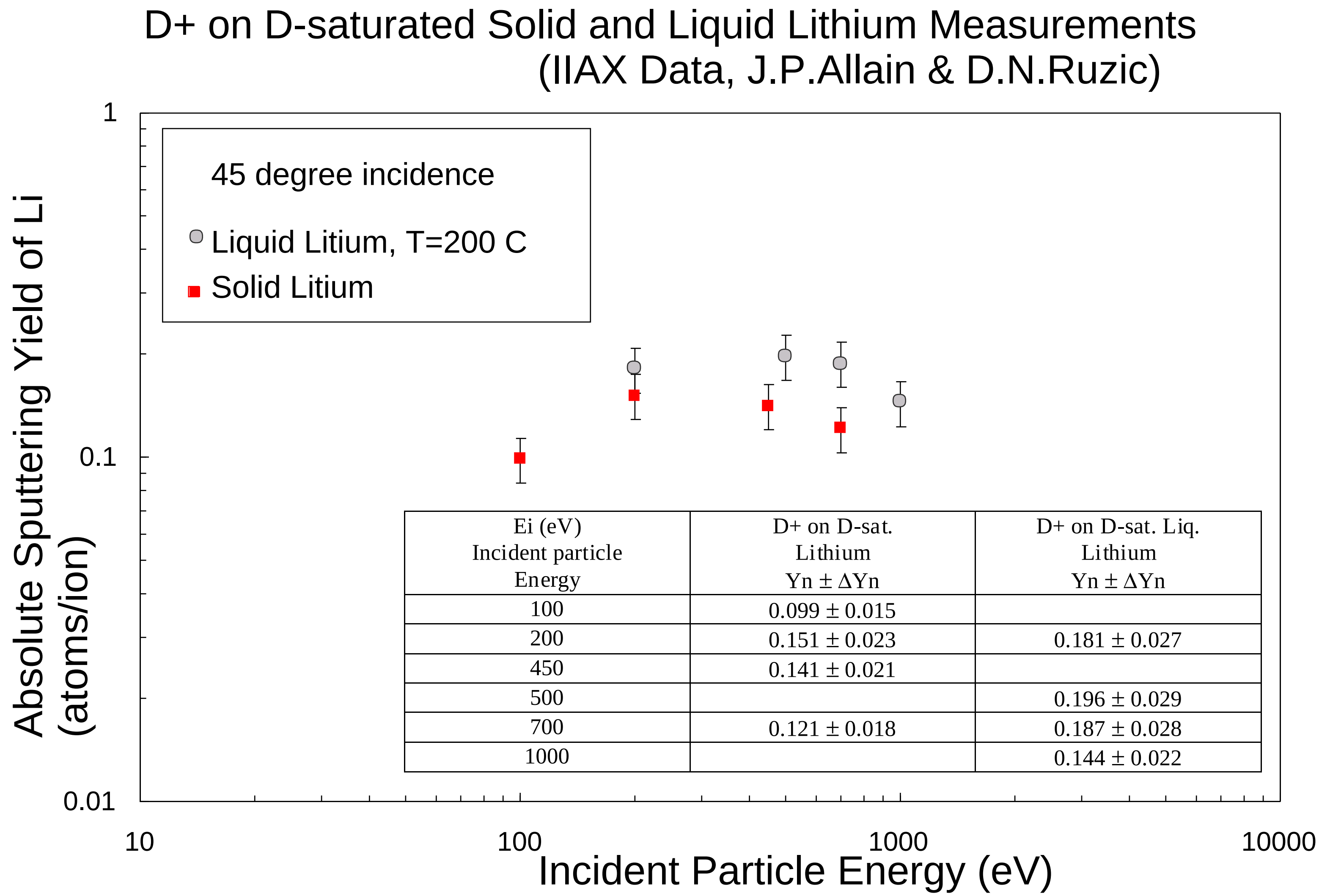


	Average Ion Range	
Angle	at 1 keV	at 2 keV
0	677 A	605 A
45	576 A	593 A
65	458 A	547 A

For 1 keV deuterium ion more than 150 Li monolayers participate in absorption.

D+ sputtering on Li

(http://starfire.ne.uiuc.edu/iiax/iiax.html, page 33)

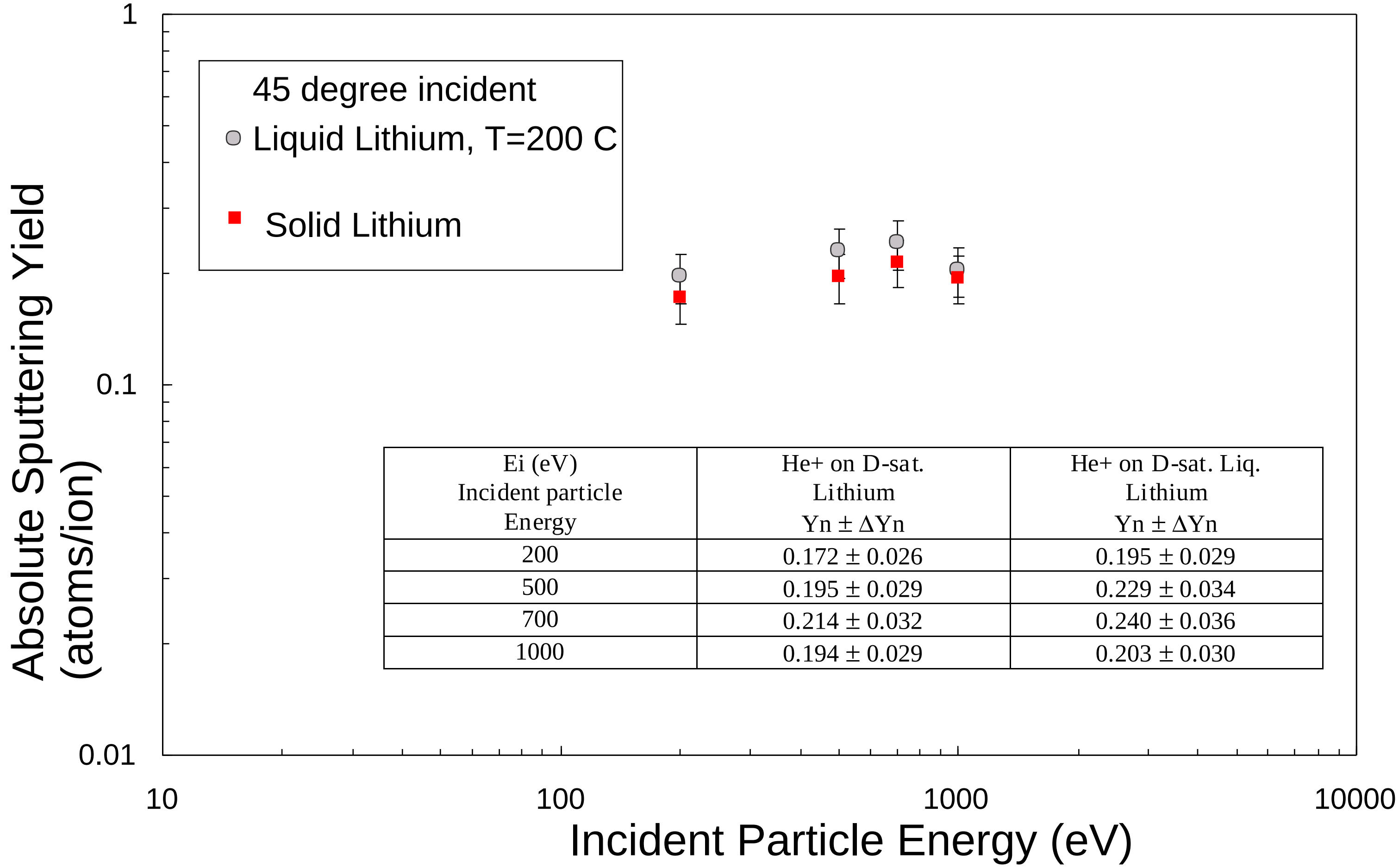


Ei (eV) Incident particle Energy	D+ on D-sat. Lithium Yn ± ΔYn	D+ on D-sat. Liq. Lithium Yn ± ΔYn
100	0.099 ± 0.015	
200	0.151 ± 0.023	0.181 ± 0.027
450	0.141 ± 0.021	
500		0.196 ± 0.029
700	0.121 ± 0.018	0.187 ± 0.028
1000		0.144 ± 0.022

He sputtering on Li

(http://starfire.ne.uiuc.edu/iiax/iiax.html, page 34)

He+ on D-saturated Solid and Liquid Lithium Measurements (IIAX Data, J.P.Allain & D.N.Ruzic)

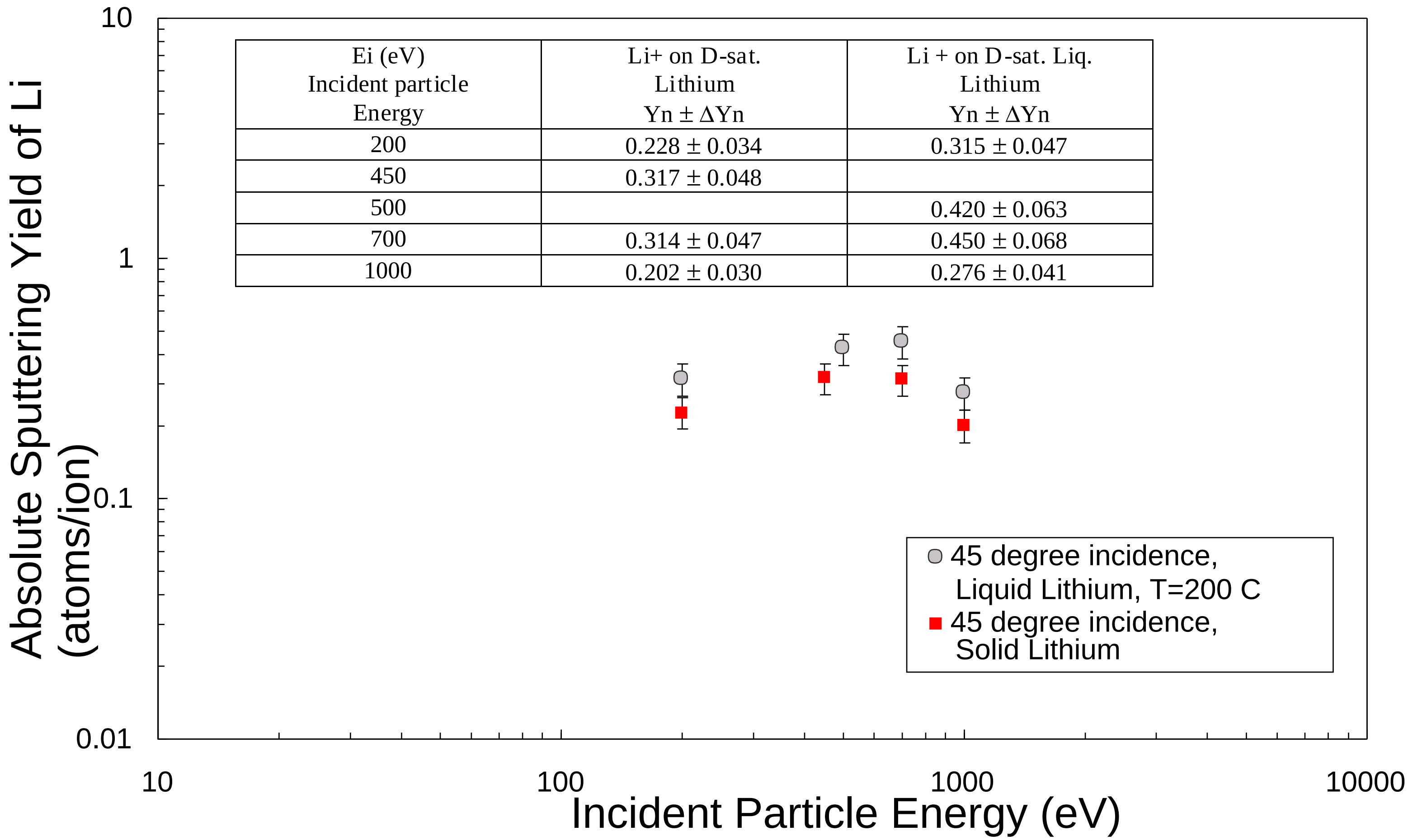


Ei (eV) Incident particle Energy	He+ on D-sat. Lithium $Yn \pm \Delta Yn$	He+ on D-sat. Liq. Lithium $Yn \pm \Delta Yn$
200	0.172 ± 0.026	0.195 ± 0.029
500	0.195 ± 0.029	0.229 ± 0.034
700	0.214 ± 0.032	0.240 ± 0.036
1000	0.194 ± 0.029	0.203 ± 0.030

Li sputtering on Li is less than 1 (no runaway)

(http://starfire.ne.uiuc.edu/pmi/IIAX%20Summary.pdf, page 32)

Li on D-saturated Solid and Liquid Lithium Measurements (IIAX Data, J.P.Allain & D.N.Ruzic)



Ei (eV) Incident particle Energy	Li+ on D-sat. Lithium $Yn \pm \Delta Yn$	Li + on D-sat. Liq. Lithium $Yn \pm \Delta Yn$
200	0.228 ± 0.034	0.315 ± 0.047
450	0.317 ± 0.048	
500		0.420 ± 0.063
700	0.314 ± 0.047	0.450 ± 0.068
1000	0.202 ± 0.030	0.276 ± 0.041

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Plasma-material interaction Group

T.D.Rognlien, M.E.Rensink (LLNL) “Liquid-Walls Temperature Limits”
(http://www.td.anl.gov/ALPS_Info_Center/alps/rogn_impur.pdf, *ALPS/APEX Meeting, Argonne Nat. Lab., May 8-12, 2000)*

Evaporation Li flux Γ

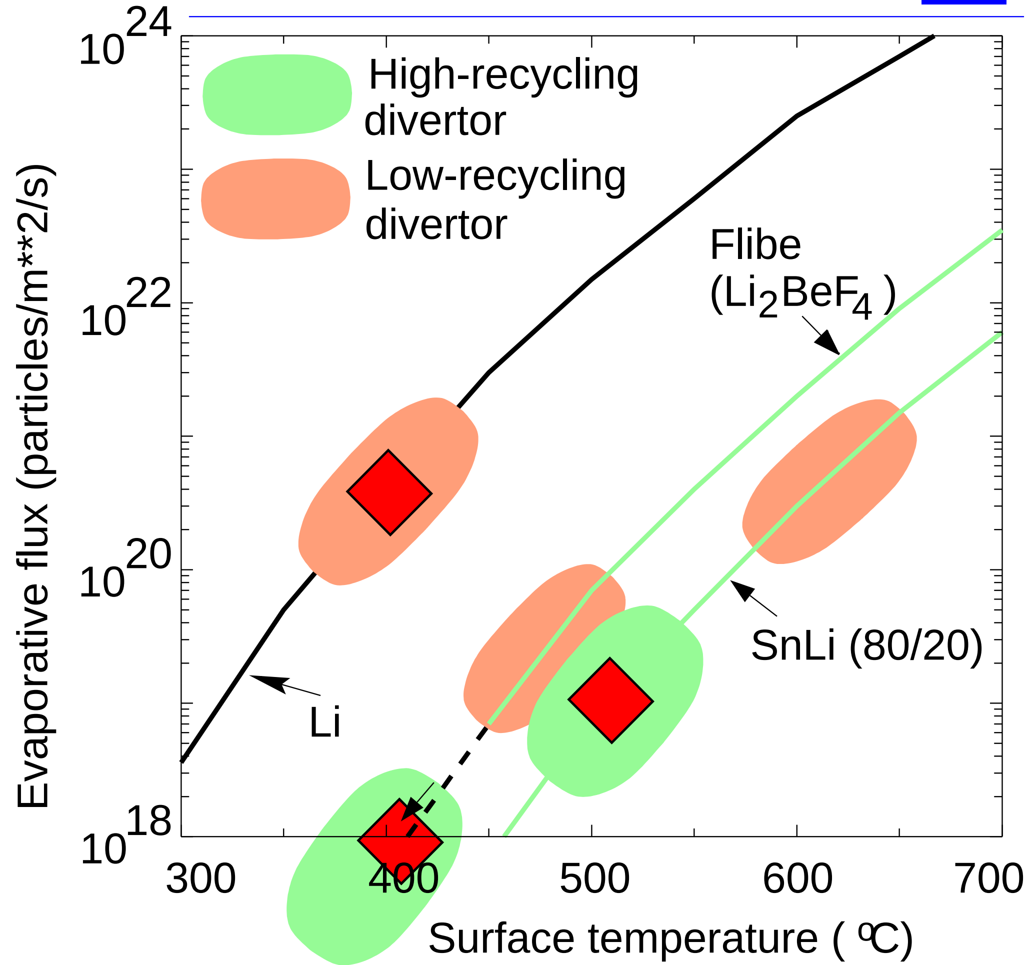
$$\Gamma \simeq 3.5 \cdot 10^{18} \cdot 10^{\frac{T^o - 300^o\ C}{50^o}} \left[\frac{1}{m^2 \cdot sec}\right]$$

At $T = 200^o\ C$

$$\Gamma \simeq 5 \cdot 10^{15} \left[\frac{1}{m^2 \cdot sec}\right]$$

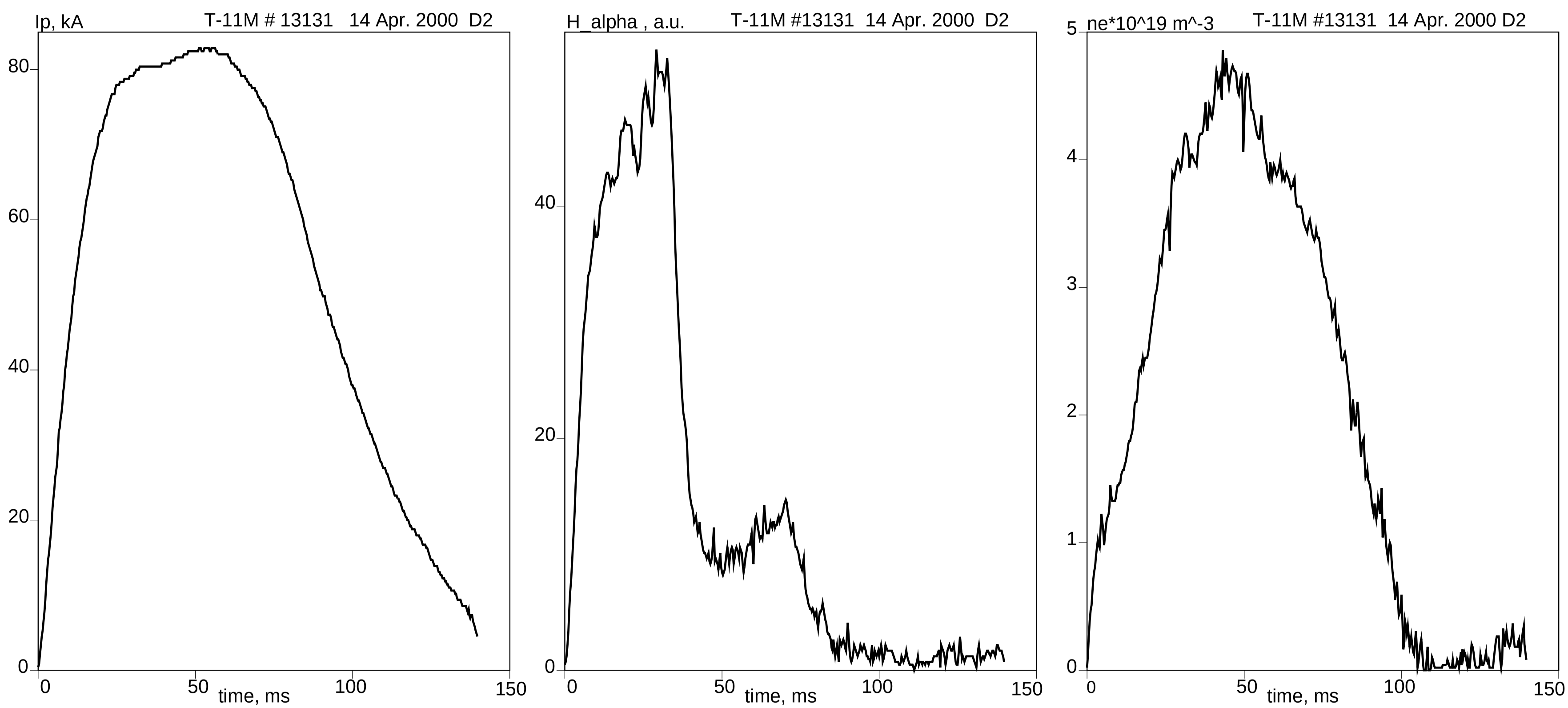
T_{Li} should be less than $400^o\ C$.

Side-wall impurity influx sets tokamak liquid temperature limits



Deuterium experiments with Li coated walls on T-11M (Ohmic heating, Li capillary porous limiter, gas puffing)

(http://w3.pppl.gov/~zakharov/Mirnov010221/Mirnov.ppt, *p.19, Exper. Seminar PPPL, Feb. 21, 2001)*

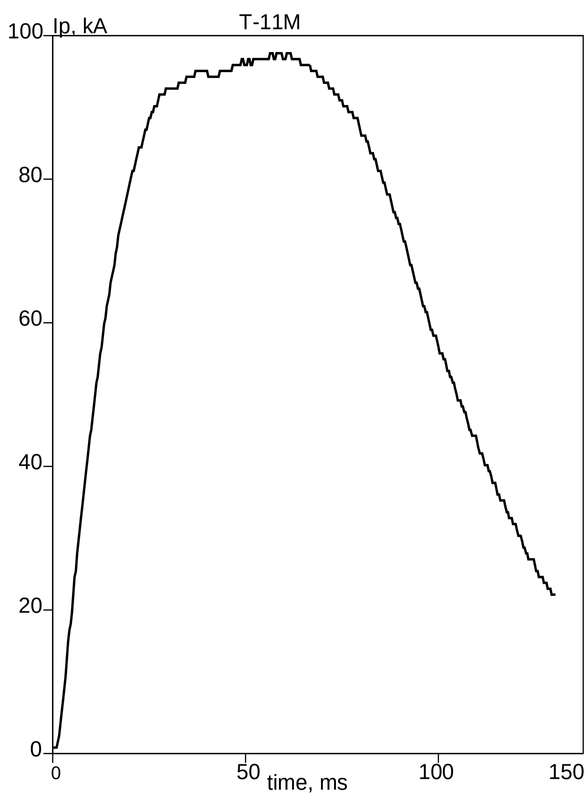


Plasma current | Gas puffing | Averaged density

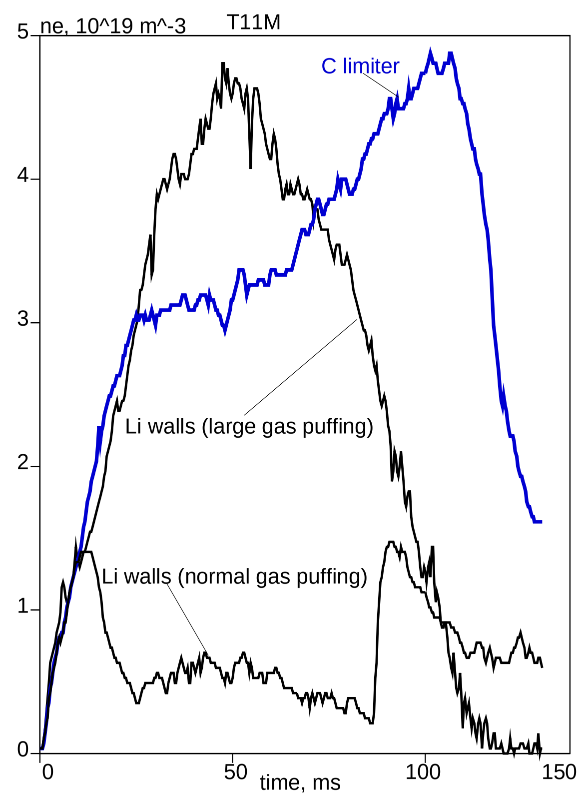
Density decays, presumably, with the particle confinement time.

Deuterium experiments with Li coated walls on T-11M.

(http://w3.pppl.gov/~zakharov/Mirnov010221/Mirnov.ppt, *p.18, Exper. Seminar PPPL, Feb. 21, 2001)*



Plasma current

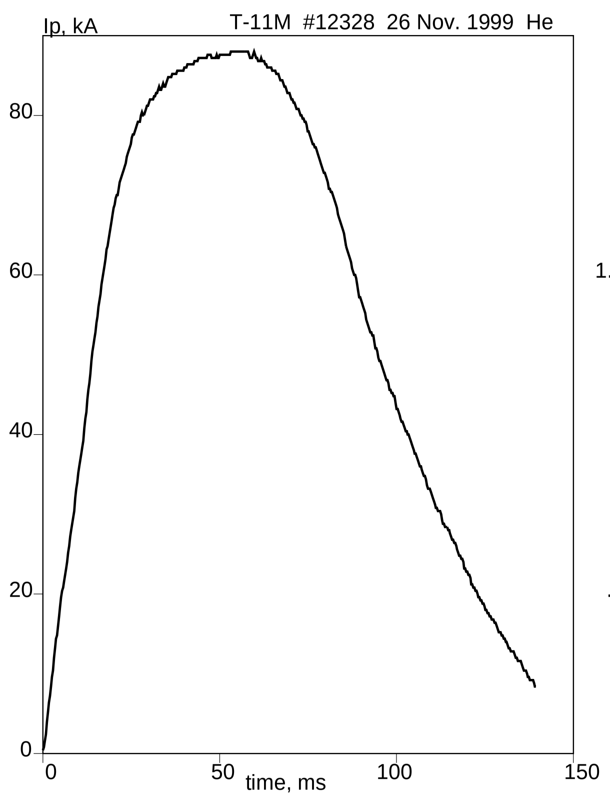


Averaged density

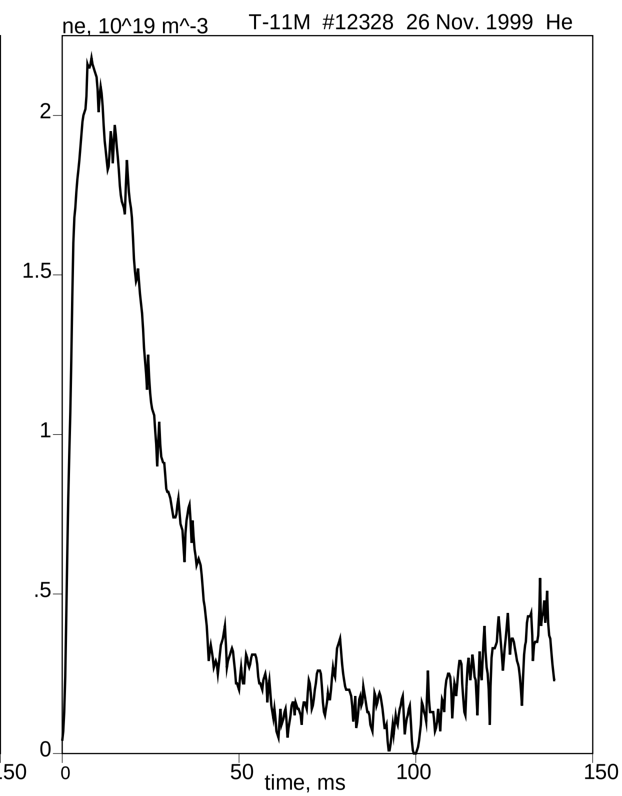
Comparison of Carbon limiter (no Li coated walls) with Li-limiter (with Li coated walls)

Helium experiments with Li coated walls on T-11M

(http://w3.pppl.gov/~zakharov/Mirnov010221/Mirnov.ppt, *p.16, Exper. Seminar PPPL, Feb. 21, 2001)*



Plasma current



Averaged density

Decay of the He plasma with Li coated walls (at lower gas puffing than for deuterium).

Increase in the wall surface temperature ΔT_{Li} depends on the power flux q_{wall} as

$$\boxed{\Delta T_{Li} = q_{wall}\sqrt{\frac{4t_{exposure}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{exposure}}{\rho c_p}},}$$

where κ is the thermoconductivity, ρ is the density, c_p is the heat capacity, and $t_{exposure}$ is the exposure time.

Two types of LiWalls:

1. Lithium (sub-millimeter) coated copper walls for experimental machines.
2. Intense liquid lithium streams ($\simeq$ 20 m/sec) for tokamak-reactors.

Both have extraordinary power extraction capabilities.

Intense Lithium Streams (ILS):

$$\begin{aligned} t_{exposure} &\equiv t_{flight}, \quad (k_T \rho c_p)_{Li} = 1.00 \left[\frac{J^2}{sec \cdot K^2 cm^4} \right], \\ \Delta T_{Li} &= 200^o \frac{q_{wall}}{3.5\ MW/m^2} \sqrt{4 t_{flight}}, \\ d_{skin} &= 2.4 \sqrt{4 t_{flight}} \text{ mm.} \end{aligned} \tag{2.3}$$

Intense lithium streams ($t_{fight} \simeq 0.25$ sec) have reactor relevant power extraction capabilities (even with no vortices in the streams)

$$\boxed{q_{wall} \simeq 3.5 \text{ MW/m}^2, \quad (+14 \text{ MW/m}^2 \text{ in neutrons}),}$$

while keeping wall heating low, $\Delta T < 200^o$ C.

E.g., for a middle size tokamak-reactor

$$\boxed{R = 6\ m, \quad a = 1.6\ m, \quad P_{wall} = 4\pi^2 R a q_{wall} \simeq 1.3\ GW}$$

Basic properties of copper:

1.*	Atomic mass	63.546
2.*	Mass density	8.96 $\frac{g}{cm^3}$
3.*	Melting temperature	1083 C^o
4.*	Boiling temperature	2543 C^o
5.*	Conductivity σ at 20^o C	59.4$\cdot 10^6$ $\frac{1}{\Omega \cdot m}$
5a.*	Conductivity σ at 400^o K	45.8$\cdot 10^6$ $\frac{1}{\Omega \cdot m}$
6.*	Heat capacity c_p at 400 ^{o} K	397.5$\frac{J}{kg \cdot K}$
7.*	Thermal conductivity k_T at 400^o K	393$\frac{W}{m \cdot K}$

[*] "Handbook of Physical Quantities", Ed. by Igor S.Grigoriev and Evgenii Z. Melnikov, Russian Research Center "Kurchatov Institute", Moscow, Russia. CRC press, Boca Raton, New York, London, Tokio (ISBN 0-8493-2861-6)

For lithium coated copper shell

$$\boxed{\Delta T_{Li} = q_{wall}\sqrt{\frac{4t_{exposure}}{\pi\kappa\rho c_p}}, \quad d_{skin} \equiv \sqrt{\frac{\kappa t_{exposure}}{\rho c_p}},}$$

Copper in comparison with Li has much higher heat tranport

$$(k_T\rho c_p)_{Cu} \simeq 14.00\left[\frac{J^2}{sec\cdot K^2 cm^4}\right] \simeq 14\,(k_T\rho c_p)_{Li}\,. \qquad (2.4)$$

For the same $\Delta T_{Li} = 200^o$ C, the time of exposure is determined by

$$\boxed{t_{exposure} \simeq 3.5\left(\frac{3.5\ \left[\frac{MW}{m^2}\right]}{q_{wall}}\right)^2 \text{ sec}}$$

Copper shell allows to have ΔT_{Li}, at least, twice bigger than 200^o C.

Solid lithium coated copper walls give reactor relevant capacities to experimental research macines in both

- particle control, and
- power extraction from the plasma

Even with no active cooling the operation time could be

- 1-4 minutes for the thermal flux $q_{wall} \simeq 1$ MW/m^2 (5 times greater than in ITER), and
- 3.5-15 seconds for $q_{wall} \simeq 3.5$ MW/m^2 (or 17.5 MW/m^2 of full wall loading).

In terms of plasma physics,

LiWall concept has a transparent path

starting from small scale circular (copper shell) cross-section tokamaks

to the (minutes long) power reactor regime

3 Confinement and stability in low recycling regime

Plasma gettering by LiWalls leads to the high plasma edge temperature

$$\left(\frac{5}{2}\Gamma T\right)_{edge} = \int\int\int_0^a P_E dv, \quad T_{edge} = \frac{\int\int\int_0^a P_E dv}{\frac{5}{2}\Gamma} \quad P_E - \text{heat source.}$$

With LiWalls the major energy loss channel, i.e., thermo-conduction, can be eliminated (S. Krasheninnikov, Dec. 1998).

Plasma profiles are determined by the particle continuity equation

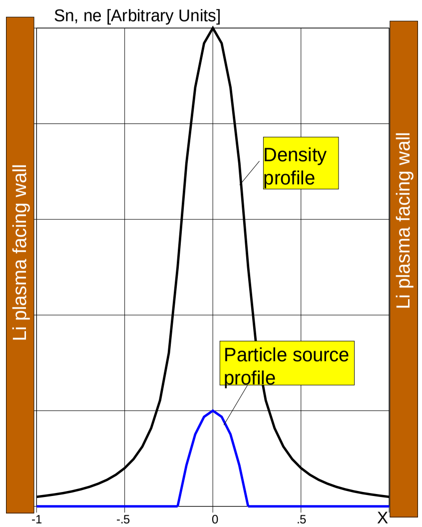
$$\Gamma \equiv Snv = const = (\Gamma)_a$$

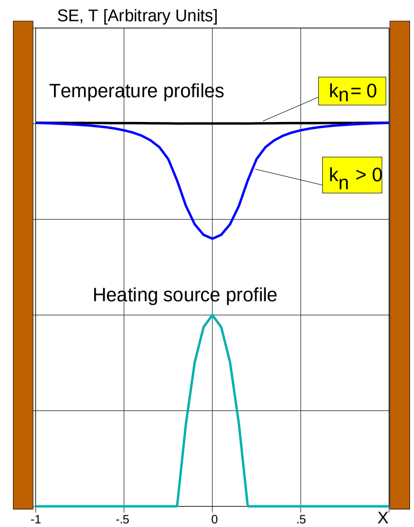
and by the energy balance

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int\int\int_0^r P_E dv$$

Two together determine flattened temperature profiles in the plasma.

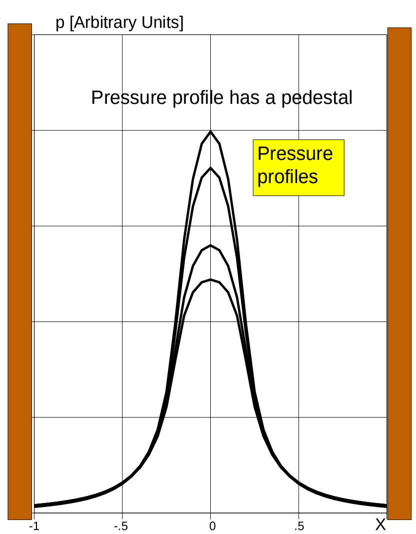
In non-recycling regime $\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P dv$

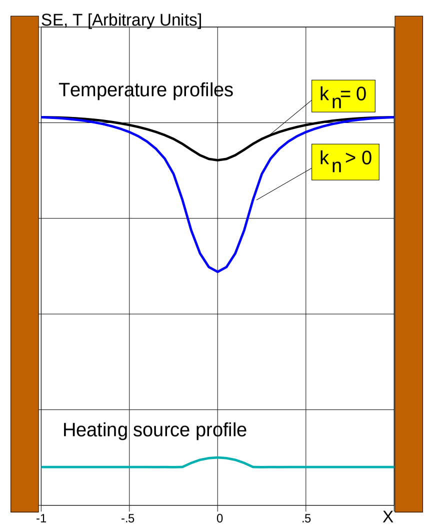




DENSITY profile (left) is predetermined by the central fueling.

TEMPERATURE profile (right) adjusts itself in order to ELIMINATE the thermo-conduction.

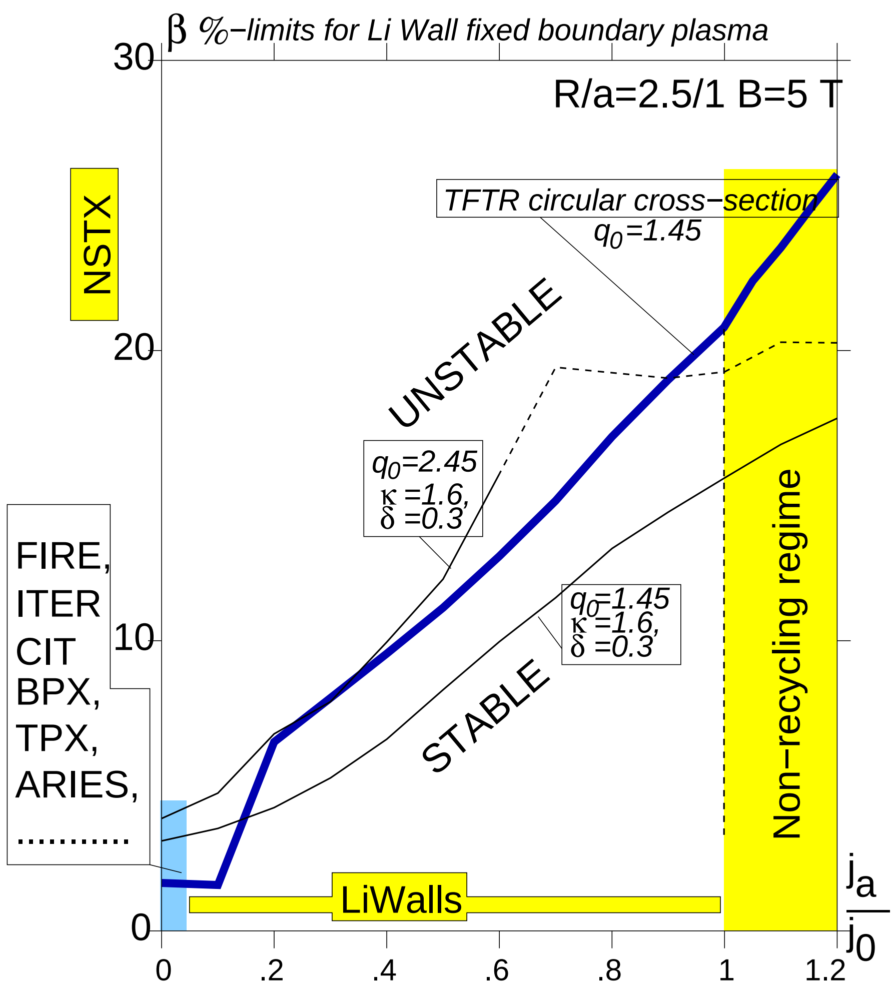




PRESSURE profile (left) has a jump at the plasma boundary.

TEMPERATURE profile (right) eliminates the thermo-conduction irrespective to the heat source profile.

Fixed boundary plasma & flatenned temperature profile results in a new core MHD regime:



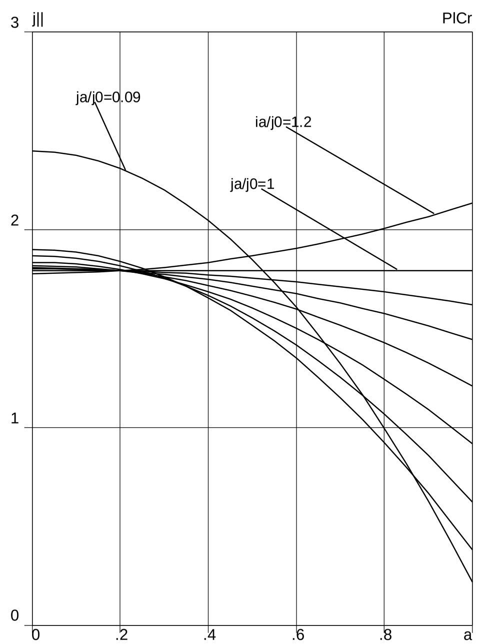
- no sawtooth oscillations;
- no Troyon limit;
- the second stability core;

β - limits for the second stability regime

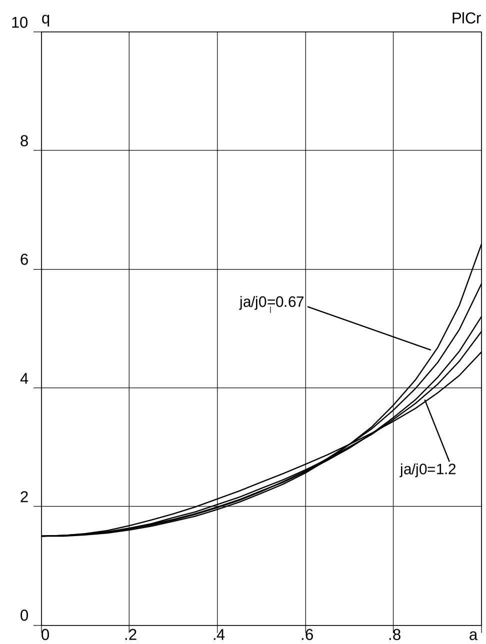
- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON,ESC)
- current density with an edge pedestal

$$\mathrm{j}_{\|} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

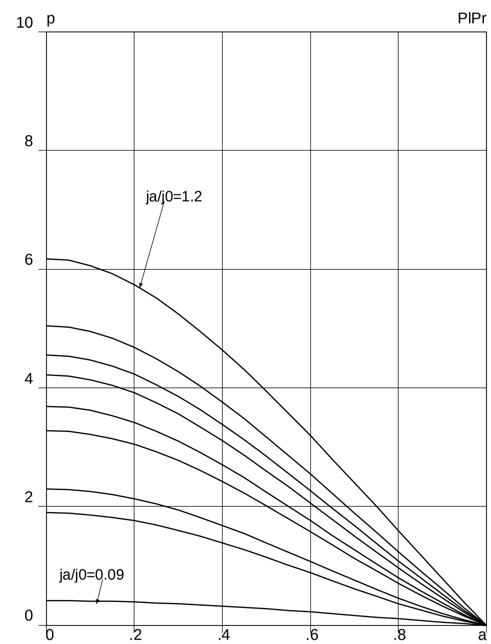
Current density profiles has been chosen as determined by the classical Ohm's law



$j_{||}$-profiles



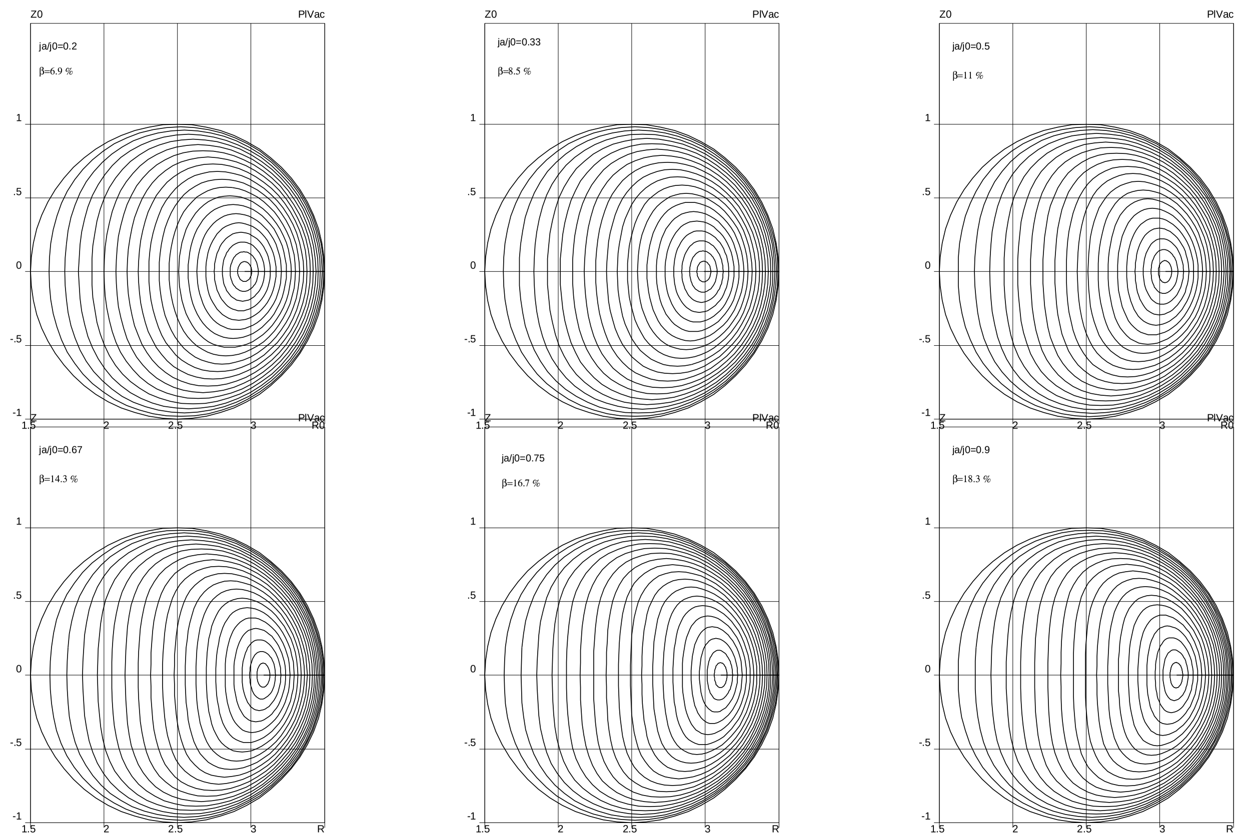
q-profiles



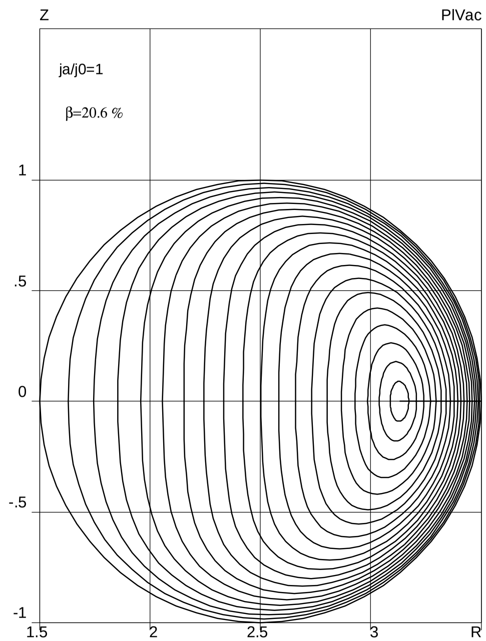
p-profiles

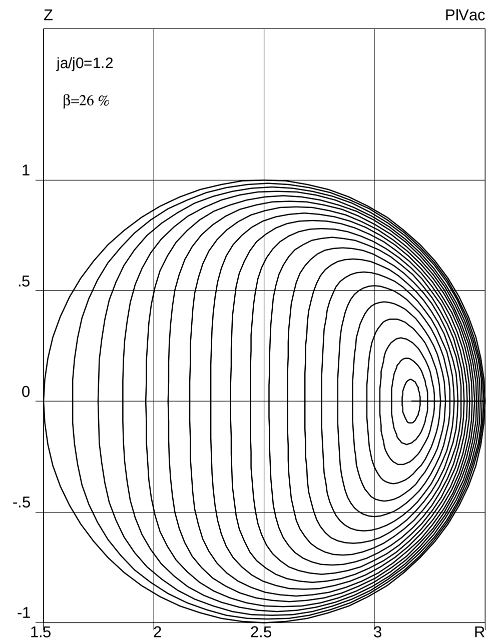
$$\frac{dp}{d\Psi} = const, \quad a = \sqrt{\frac{\Phi}{\Phi_{edge}}}, \quad \Phi \text{ is the toroidal flux.} \qquad (3.1)$$

Marginally stable high β configurations



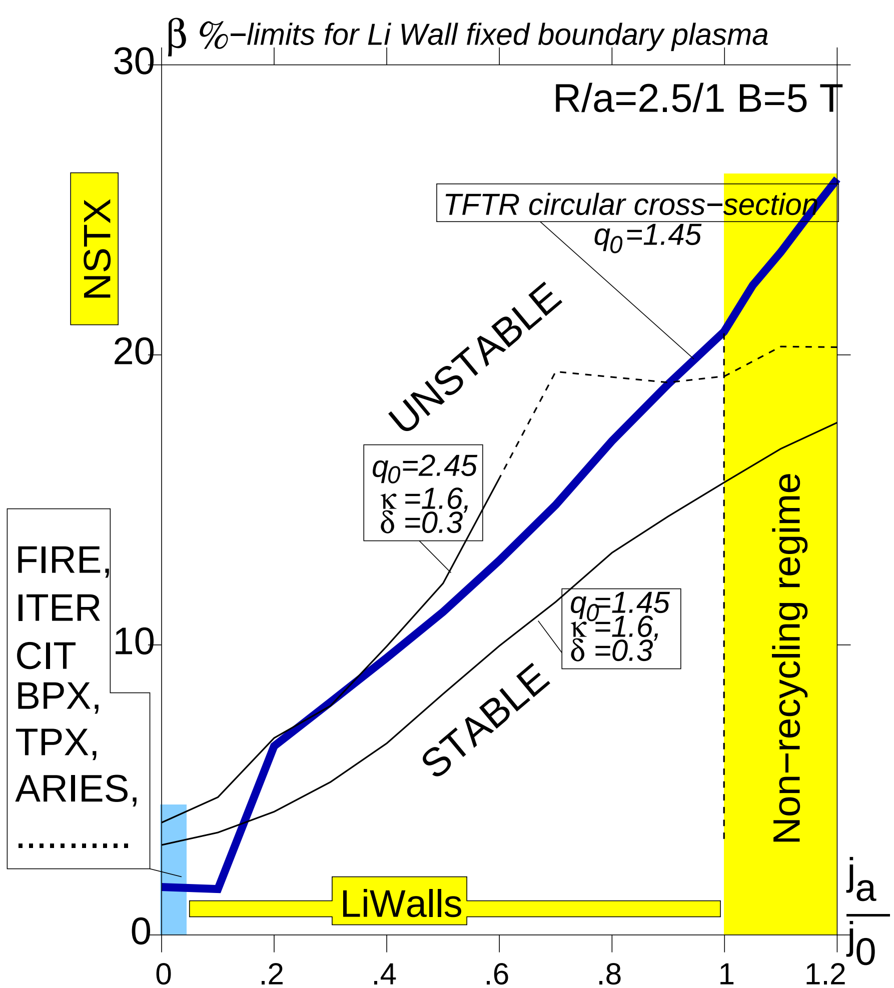
Marginally stable high β configurations





Configurations relevant
to the non-recycling regime

Fixed boundary plasma & flatenned temperature profile results in a new core MHD regime:



- no sawtooth oscillations;
- no Troyon limit;
- the second stability core;

β - limits for the second stability regime

- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON,ESC)
- current density with an edge pedestal

$$\mathbf{j}_{\|} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

Within β limits enhancement of τ_E is very beneficial for performance.

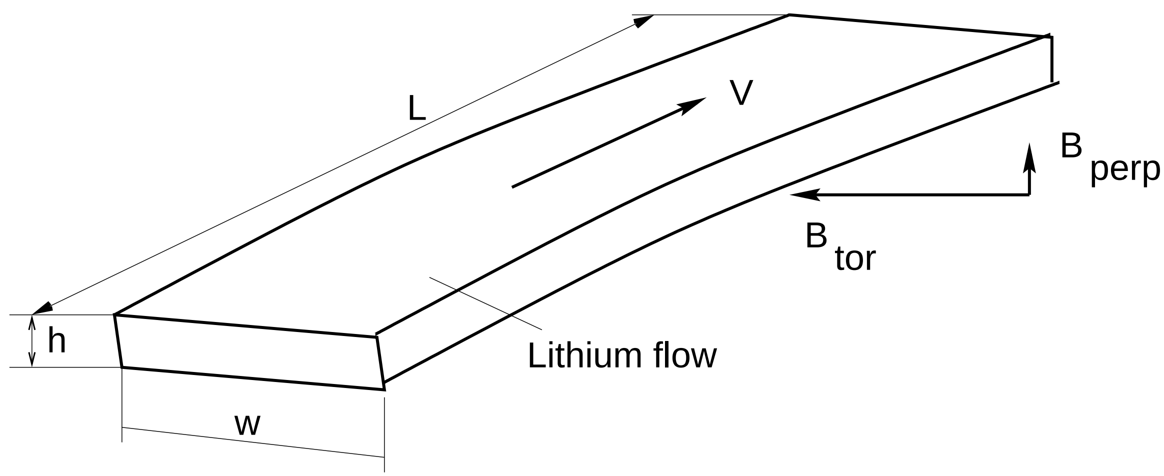
$$n \propto \tau_E, \quad nT\tau_E \propto \tau_E^2. \tag{3.2}$$

With lithium coated copper walls installed TFTR could easily pass the breakeven. Doubling τ_E would be sufficient.

4 MHD of liquid lithium. Basic Reynolds numbers.

There 3 magnetic Reynolds numbers which control lithium MHD in tokamaks

$$
\begin{aligned}
\text{dynamics}: \quad & \Re_0 \equiv \mu_0 \sigma L V, \\
\text{electro-dynamics}: \quad & \Re_1 \equiv \mu_0 \sigma h V, \\
\text{dynamics}: \quad & \Re_2 \equiv \mu_0 \sigma \frac{h^2}{L} V, \\
& \mu_0 \sigma \simeq 4 \left[\frac{sec}{m^2} \right].
\end{aligned} \tag{4.1}
$$



Characteristic flow parameters:

$$\begin{aligned} V = 20\ m/sec &\rightarrow \rho\frac{V^2}{2} \simeq 1\ [atm], \\ B = 1\ T &\rightarrow \frac{B^2}{2\mu_0} = 4\ [atm], \\ B = 5\ T &\rightarrow \frac{B^2}{2\mu_0} = 100\ [atm]. \end{aligned} \tag{4.2}$$

Dynamic pressure losses are determined by $\Re_0$ and $\Re_2$

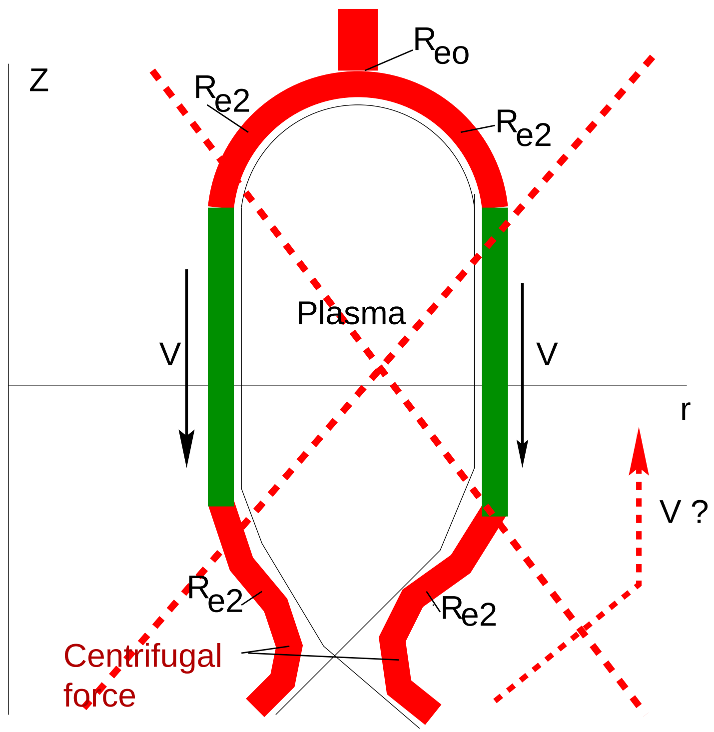
$$\begin{aligned} \Re_0 : \quad \Delta\rho\frac{V^2}{2} &= \mu_0\sigma L V\frac{B_\perp^2}{2\mu_0}, \\ \Re_2 : \quad \Delta\rho\frac{V^2}{2} &= \mu_0\sigma\frac{h^2}{L}V\Delta\frac{B_\parallel^2}{2\mu_0}, \\ \mu_0\sigma &\simeq 4\ \left[\frac{sec}{m^2}\right]. \end{aligned} \tag{4.3}$$

Magnetic fields from the currents in the stream are determined by $\Re_1$

$$\Re_1 : \quad B_{||out} - B_{||in} = \mu_0\sigma h V B_\perp. \tag{4.4}$$

Lithium “water-falls” will not flow through the tokamak strong toroidal field

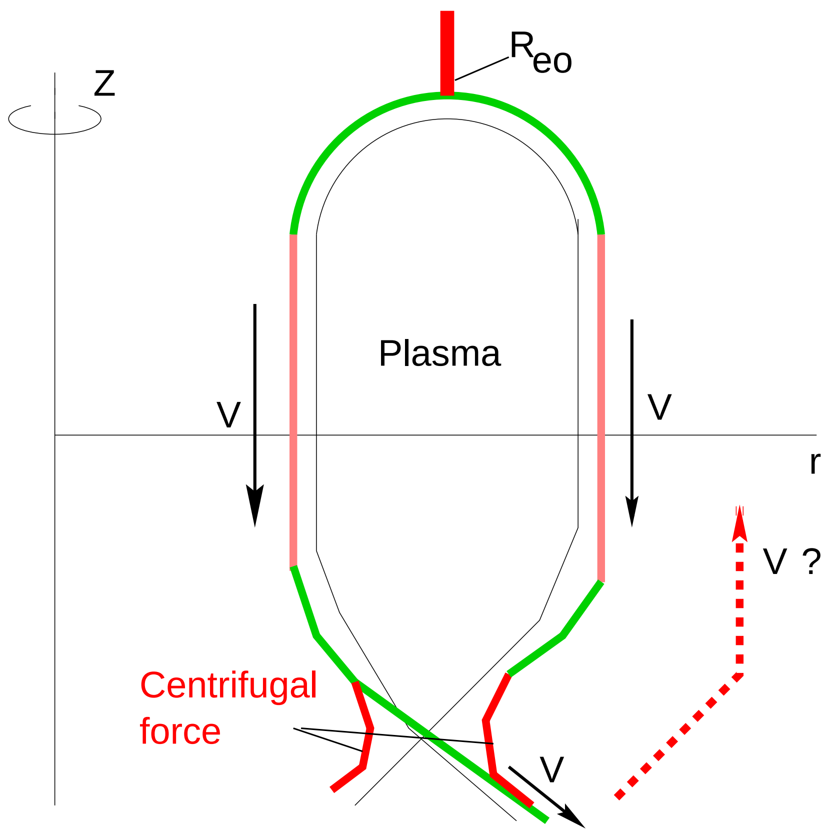
$$\begin{aligned} &h = 0.1\,m, \quad L_1 \simeq 0.2\,m, \quad L_2 \simeq 3\,m, \quad V > 2-5\,[m/sec],\\ &\Re_0 = 4L_1 V => 1.6,\\ &\Re_2 = 4\frac{h^2}{L_2}V = 4\frac{h}{L_2}(hV) \simeq 0.01 - 0.025. \end{aligned} \tag{4.5}$$



$$\boxed{\rho\frac{V^2}{2} \ll \Re_2 \Delta \frac{B_{tor}^2}{2\mu_0}}$$

Momentum driven thin walls have many of unresolved problems in lithium MHD

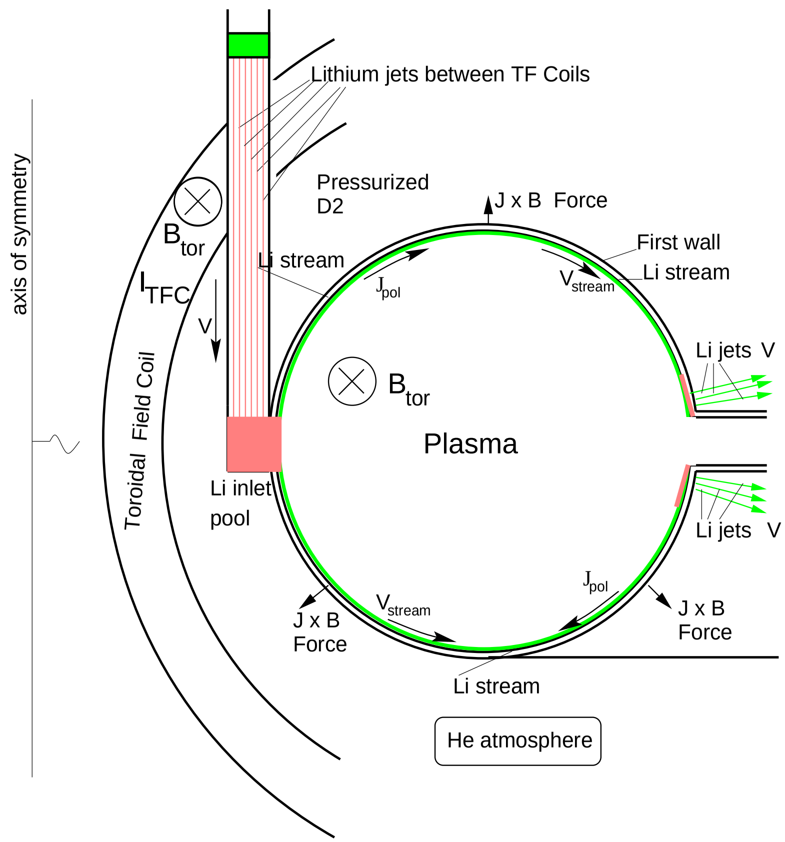
$$h = 0.01\ m, \quad L_1 \simeq 0.02\ m, \quad L_2 \simeq 3\ m, \quad V \simeq 20\ [m/sec],$$
$$\Re_2 = 4\frac{h^2}{L_2}V \simeq 1.3 \cdot 10^{-4}. \tag{4.6}$$



$$\boxed{\Re_0 = 1.6, \quad \rho\frac{V^2}{2} < \Re_0\frac{B_{pol}^2}{2\mu_0}}$$

Magnetic propulsion opens the possibility for intense plasma facing lithium streams in tokamaks

$$p_{\mathrm{j\times B}}|_{inlet} - p_{\mathrm{j\times B}}|_{outlet} \gg \Re_2 \frac{B_{tor}^2}{2\mu_0}, \quad \Re_2 \equiv \mu_0 \sigma \frac{h^2}{R} V \simeq 0.0015$$



- Driving electro-magnetic pressure

$$p_{\mathrm{j\times B}}|_{outlet} > 1\ atm$$

$$p_{\mathrm{j\times B}}|_{inlet} - p_{\mathrm{j\times B}}|_{outlet} \simeq 1.5 - 3\ [atm$$

- Flow parameters

$$V \simeq 20\ m/sec, \quad h \simeq 0.01\ m$$

- Magnetic Reynolds numbers

$$\Re_1 \equiv \mu_0 \sigma h V \simeq 0.8, \quad \Re_2 \simeq 0.0015$$

- Stream are robustly stable due to centrifugal force

$$\rho \frac{\langle V^2 \rangle}{2} > \frac{a}{2R} p_{wall} n_r$$

Invention of magnetic propulsion (Dec. 1998) introduced a new "resistive wall" concept with the $m = 1$-like flow pattern of Intense Li Streams.

Centrifugal stabilization of streams (against "sausage" inst.)

$$\rho\frac{\langle V^2\rangle}{2} > \frac{a}{2R} p_{wall} n_r. \qquad (4.7)$$

Circular cross-section tokamaks are the most suitable for Intense Li Streams

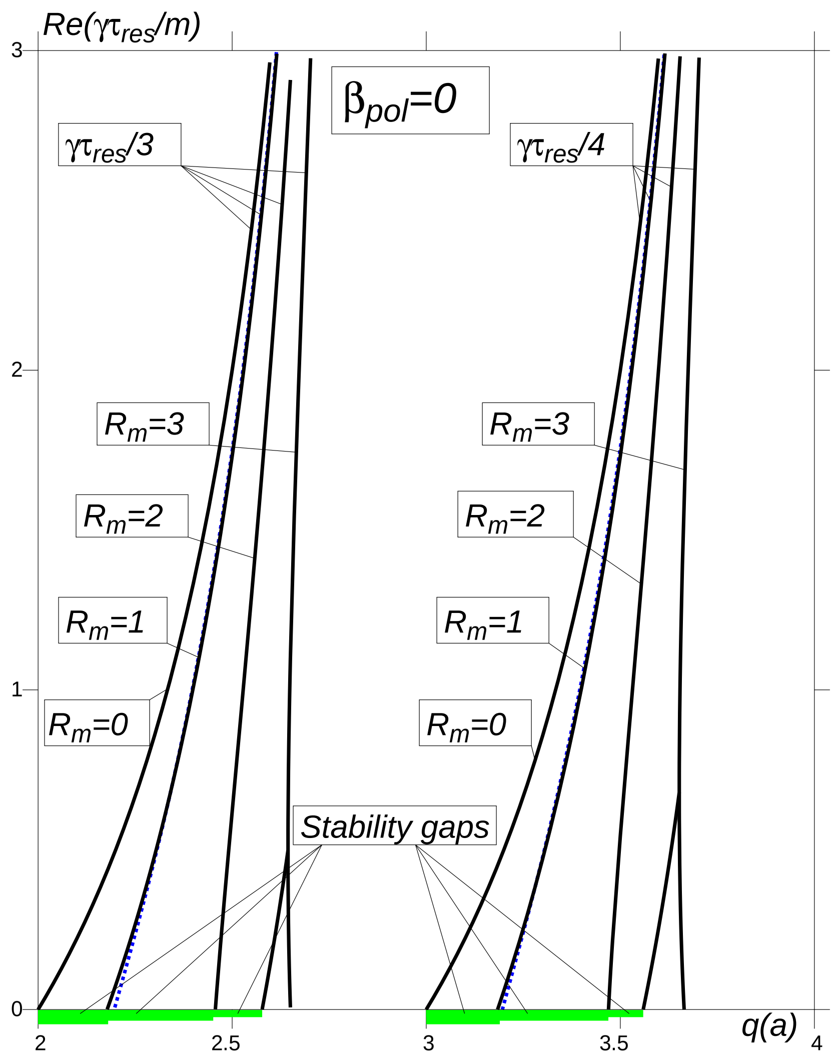
Being insensitive to electromagnetic forces and stable, Li Streams contribute positevely to the plasma stability over the full range of frequencies.

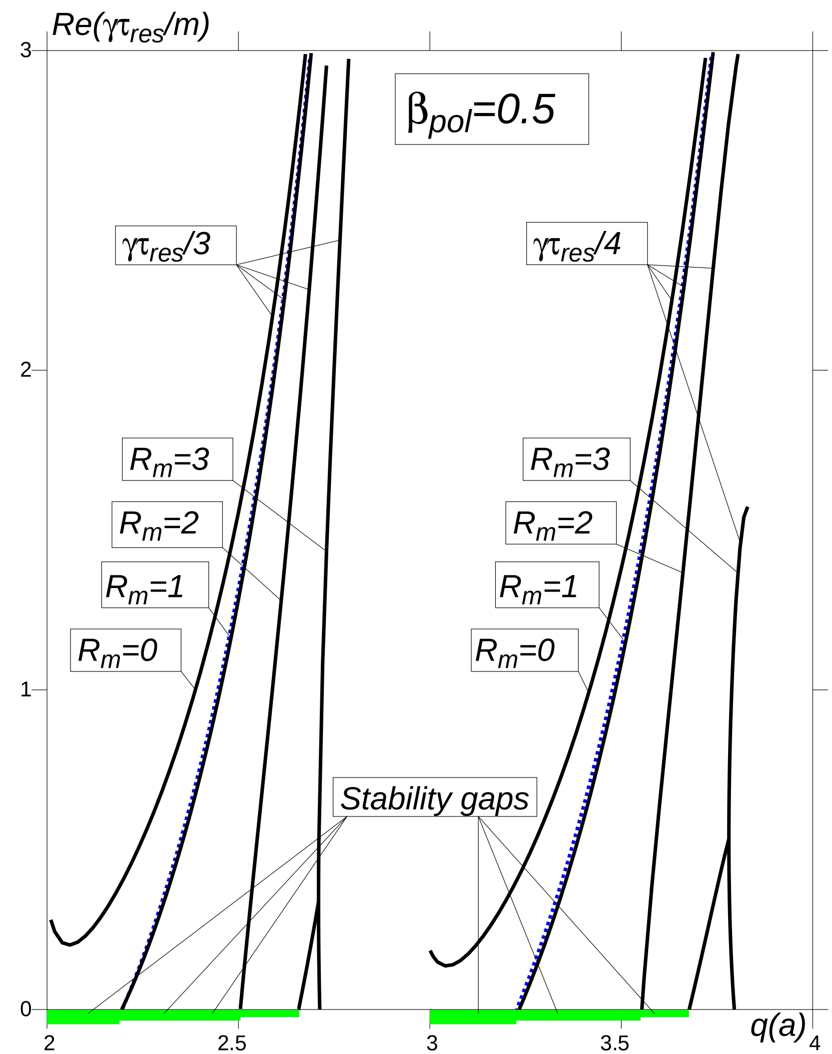
The theory was completed and significant stabilization can be exected at

$$\Re_1 = \mu_0 \sigma h V > 1. \qquad (4.8)$$

Projected value for the LiWall reactor $\Re_1 = 0.4 - 0.8$.

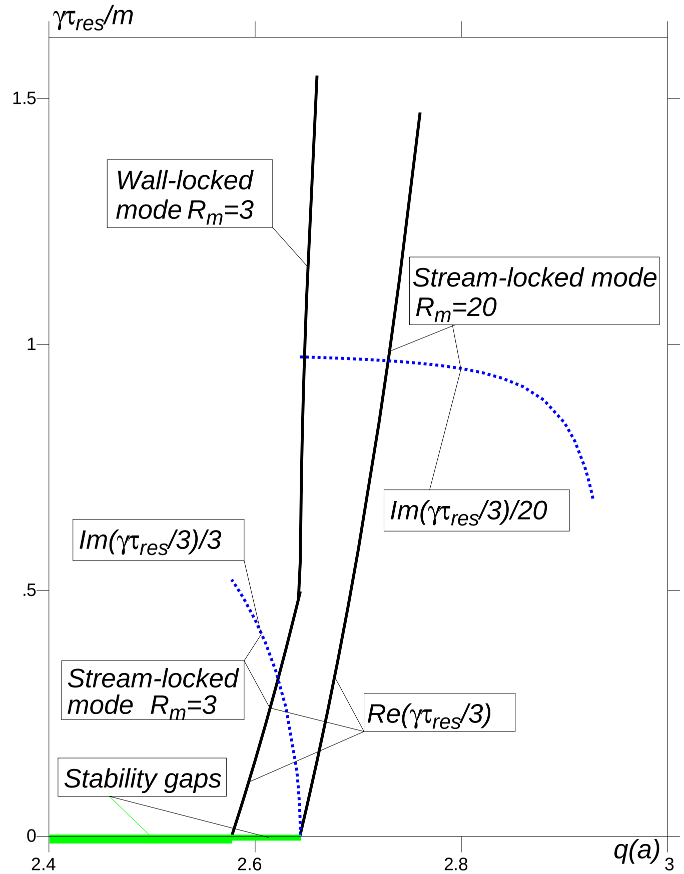
Stability gaps are insensitive to m-number. Finite β can be stabilized.

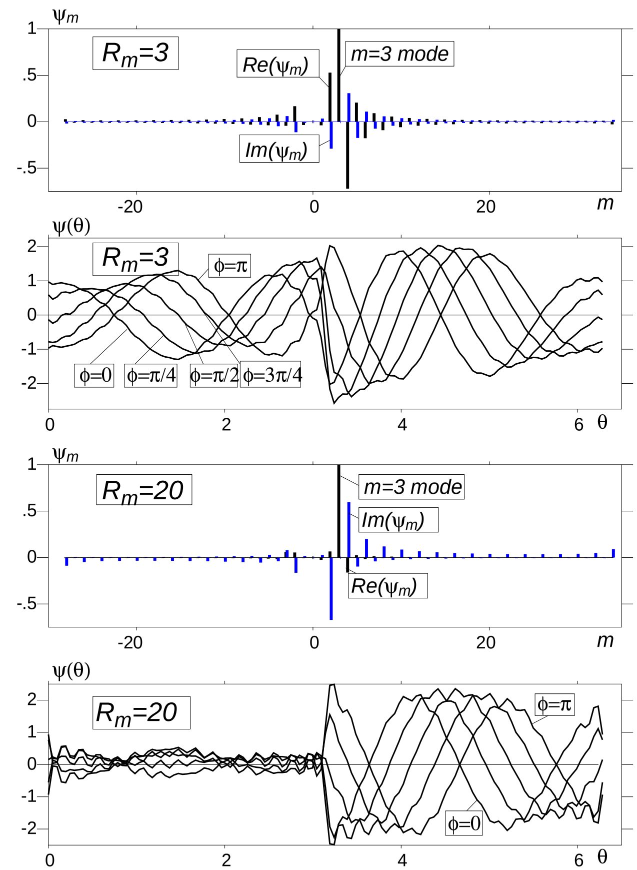




Resistive wall mode is well affected by the flow.

Flow-locked mode determines limits of stabilization.

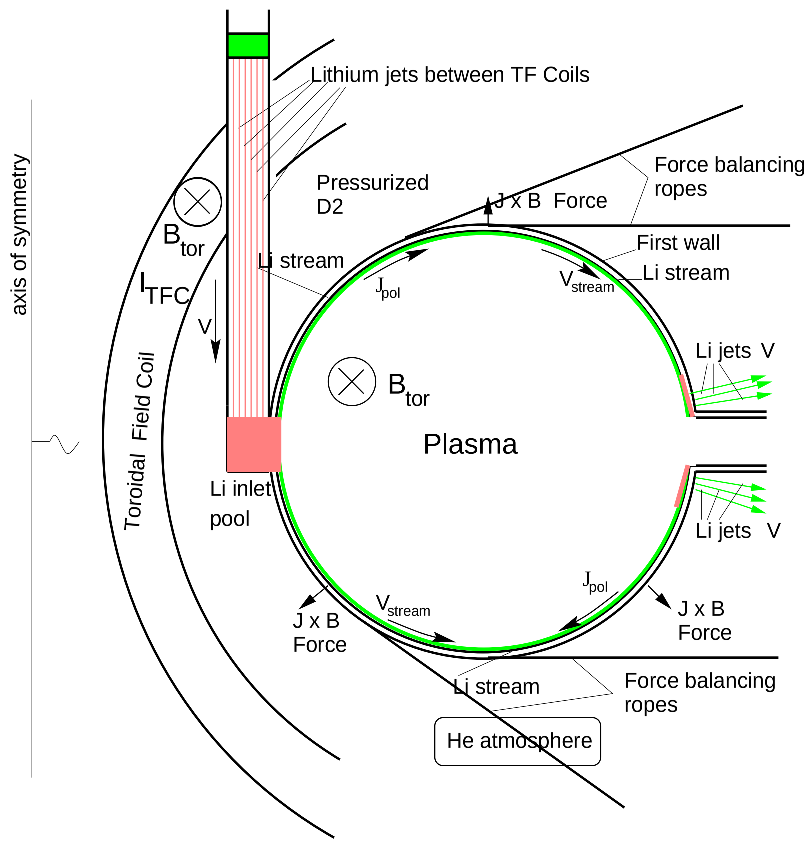




5 Yacht Sail approach for tokamak-reactors.

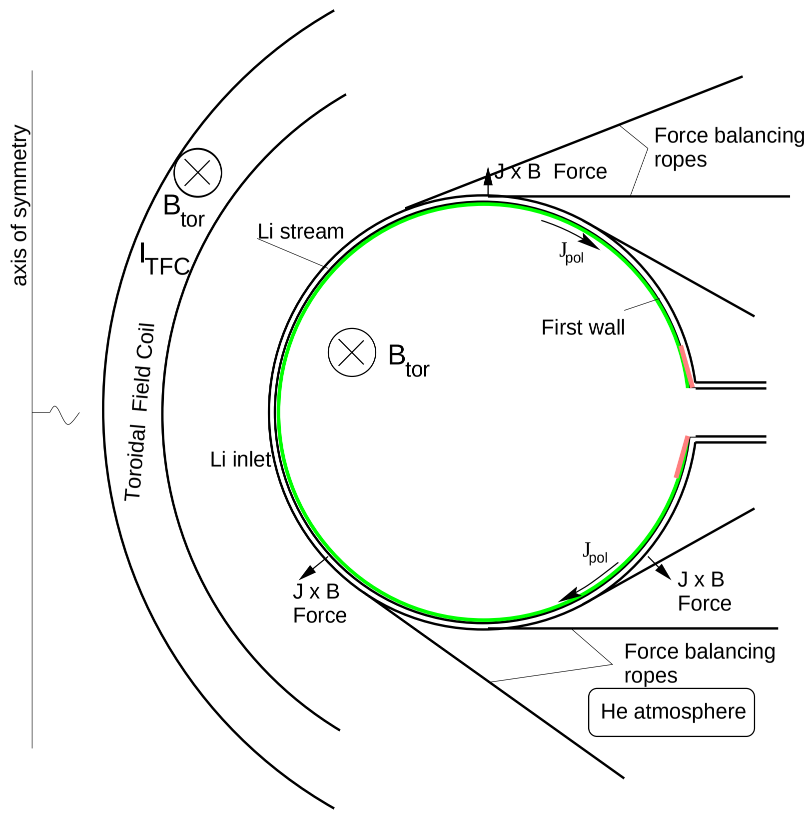
Intense Li Streams affect the very fundamentals of tokamak reactor desing.

Electrodynamic pressure creates a stable situation for the first wall.



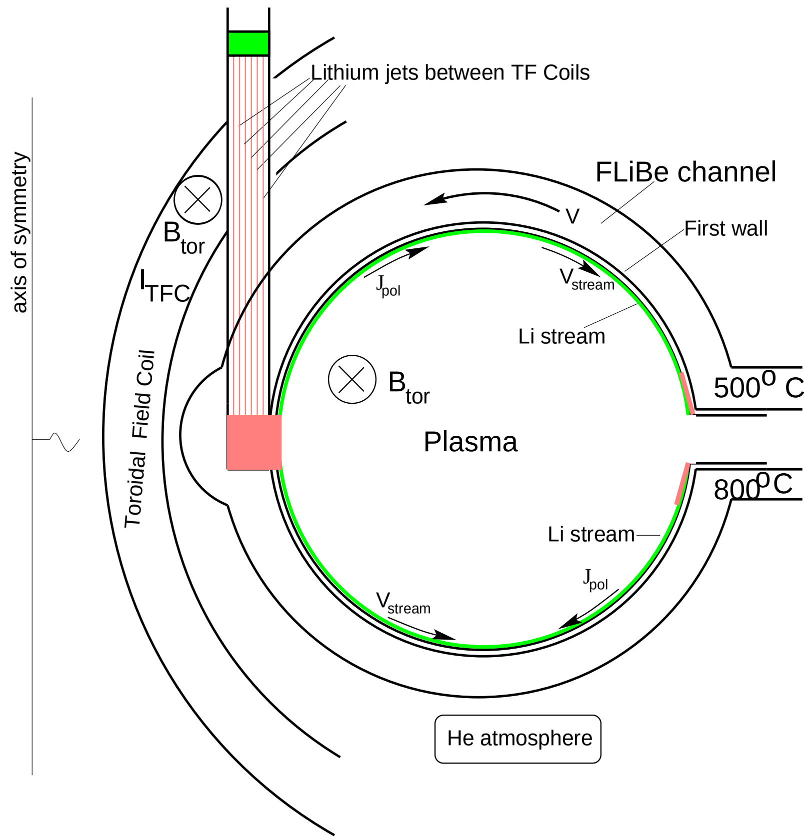
- Guide wall works against expansion $\Longrightarrow$
- Guide wall can be made as a thin shell (like a car tire).
- Inner surface is sealed by the lithium streams (insensitive to cracks) $\Longrightarrow$
- Vacuum barrier can be moved to the plasma boundary (giving access to the neutron zone).

Dynamic balancing of the first wall



- Radial component of the electromagnetic force can be balanced by the set of external wire ropes
$$\left(p_{\mathrm{j}\times\mathrm{B},outlet}\frac{r^2_{outlet}}{r^2} - p_{atm}\right)\frac{r}{r_{inlet}} = Td,$$
where T is the tension of ropes, $d(r)$ is the total thickness as a function of position of the touch point.
- Ropes are the best solution to withstand plasma disruptions.
- Ropes can be made from Be (non-activatable).
- Ropes can be replaced during reactor operation.

Intense Li Streams + $(LiF)_n(BeF_2)$ (i.e., FLiBe) make an excellent FW/blanket combination (S.Zinkle, B.Nelson, ORNL)



Lithium streams keep the wall temperature below melting point of FLiBe

$$T_{wall} \simeq 200^o - 250^o < T_{melt,FLiBe} \simeq 450^o$$

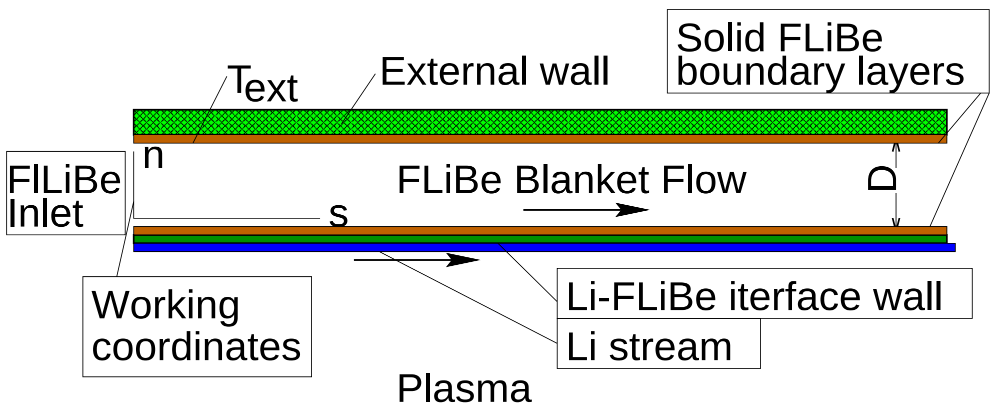
Independent of inner temperature in the chanell FLiBe has a solid boundary layer at the walls.

Even with

$$T_{FLiBe}\big|_{outlet} = 800^o\ C$$

energy losses on the side walls are $\simeq 4\%$.

Stratified geometry of the FLiBe Blanket/Lithium streams



D	m	0.1
L	m	10
V	$\frac{m}{sec}$	0.5
$S(n)$	$\frac{W}{cm^3}$	100-40
$T_{side\ wall}$	C^o	200

The radial thickness D of the channel is assumed to be much smaller than the length L of the channel. Plasma side wall temperature is kept constant by a fast Lithium flow.

Heat source S corresponds approximately to 10 MW/m^2 in neutrons.

The walls of the channel are kept below the melting point of FLiBe, so two solid salt layers are formed on the walls of the channel.
The stationary heat diffusion equation

$$\begin{aligned} \rho c_p V \frac{\partial T}{\partial s} &= \kappa T''_{nn} + S, \quad T > T_{melt}, \\ 0 &= \kappa T''_{nn} + S, \quad T < T_{melt} \end{aligned} \tag{5.1}$$

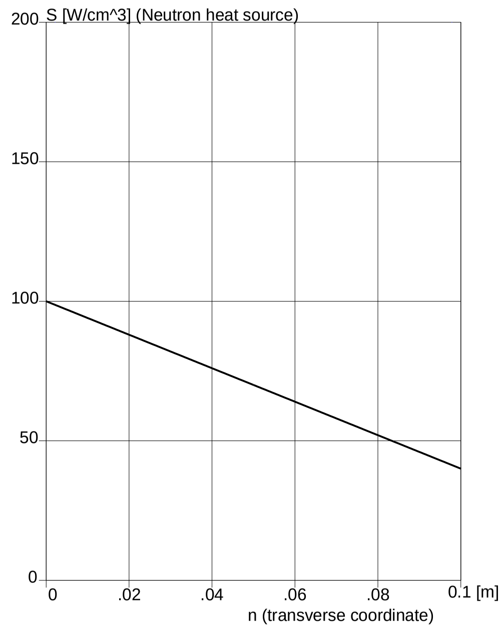
together with the matching conditions determines the temperature distribution in the flow.

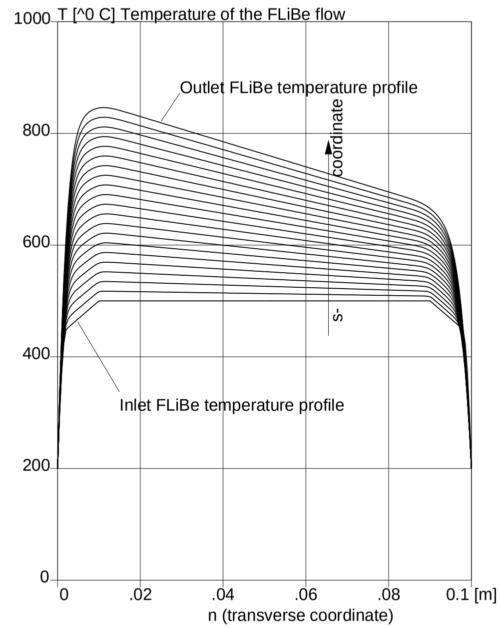
Here, ρ is the mass density of FLiBe, c_p is the heat capacity, V is the velocity of the flow, κ is the thermo-conduction.

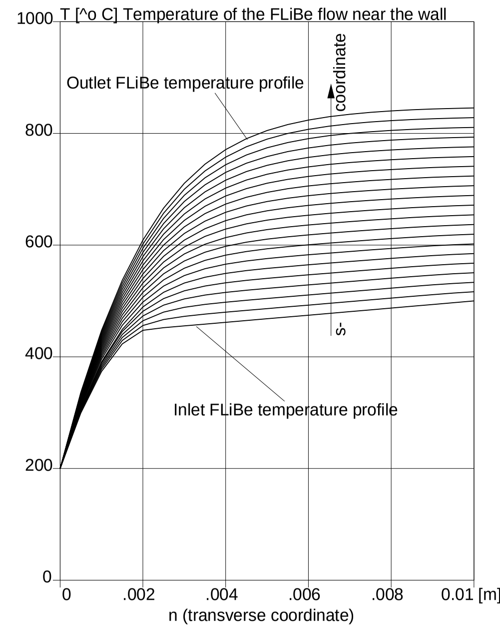
Thickness of the solid layer is determined as an eigenvalue of the problem in a self-consistent way.

FLiBe parameters		
ρ	$\frac{kg}{m^3}$	2240
c_p	$\frac{J}{kg \cdot C^o}$	2380
κ	$\frac{W}{m \cdot C^o}$	1
T_{melt}	C^o	450

Profiles of the (neutron) heat source and T in the FLiBe channel







FLiBe thermo-conduction is so small that the temperature inside the body of the flow is determined solely by the heat source power

$$\rho c_p V \frac{\partial T}{\partial s} \simeq S, \quad T > T_{melt}, \qquad (5.2)$$

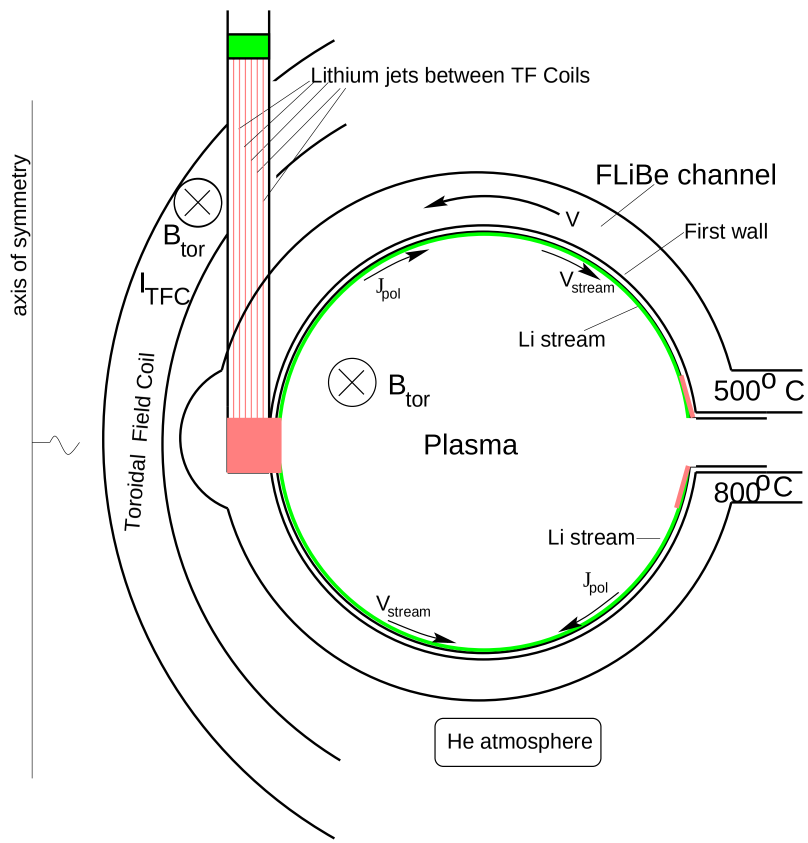
not by thermo-conduction losses.

Two boundary layers of the order of 1-3 mm are formed near walls of the channel. Inside, each of them contains a sublayer of a solid FLiBe.

In the example the averaged energy losses are $\mathbf{0.26}\ \boldsymbol{MW/m^2}$ through the plasma side wall and $\mathbf{0.16}\ \boldsymbol{MW/m^2}$ through the Toroidal Field Coil (TFC) side of the wall, which constitute approximately 4 % of the incoming neutron flux energy.

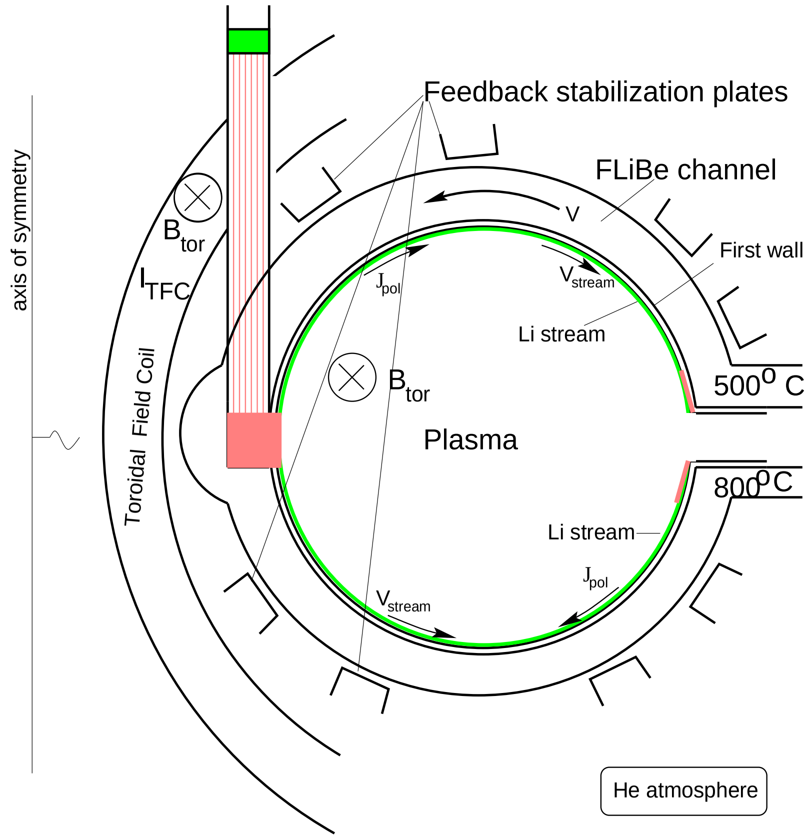
FLiBe seems to be a perfect coolant for the tokamak-reactor

It would be not crazy to think about making the vacuum chamber from the wire mesh



- wall becomes insensitive to thermal deformations $\Longrightarrow$ pulsed regime is acceptable (no high-tech for the current drive);
- deformations of the wall can be corrected on the fly (Yacht sail approach);

LiWall Tokamak is not a hostage of the requirement to be stationary.



- wire wall, presumably, can withstand the high neutron flux;
- activation is minimum in the neutron zone;
- feedback plates are protected by the FLiBe layer with still excellent electromagnetic coupling with the plasma;

6 Summary

LiWall concept

opens a "high-$\beta \cdot \tau_E$" path to the power fusion reactor

(with a lot of work to be done)

For the first time, the renewable and absorbing plasma facing walls were introduced into the tokamak research.

From the plasma physics side, lithium walls may provide

- a low recycling regime (best possible for the energy confinement);
- low-Z plasma facing surface (with a central plasma fueling and surface impurities source);
- reactor relevant power extraction capabilities from the plasma
- wall conditions, which are not sensitive to the edge plasma temperature as soon as it exceeds a certain level (about 1 keV).
- slowing down free-boundary MHD instabilities,
- etc,

LiWalls, for the first time, suggest

$\boxed{\text{the “Yacht Sail” approach for the fusion reactor}}$

as a solution to the 50 year old problem of the “first wall” in magnetic fusion.

Yacht Sail approach for the fusion reactor:

Liquid FLiBe Blanket

Intense Li plasma facing streams

Dynamically balanced thin vacuum chamber wall

low pressure and minimal ammount of activated structures in the neutron zone

high temperature of the reactor coolant

insensitivity to thermal deformations

Inductive current drive is acceptable

best envirionement for feedback RWM stabilizing coils (behind the FLiBe layer)

Additional stabilization of RWM by lithium streams

7 Does the tokamak fusion have a path ?

Citing Sean Connery

"It is impossible", *(i.e., conventional magnetic fusion, LZ)*

". . . but doable" *(if the first is recognized, LZ)*

(S. Connery, “Entrapment”, TWENTIETH CENTURY FOX and REGENCY ENTERPRISES, 1999)

8 Frequently asked questions.

While being conceptually analyzed, most of problems and issues require more theory and experimental studies.

1. Q. Is the central fueling possible ?

   A. *Remain unknown. Nevertheless:*

   (a) further research should determine how "central" the fuel injection has to be.

   (b) second, the distance between the magnetic axis and the plasma boundary in the LiWall tokamak-reactor is about 0.6-0.7 m (much smaller than in a big ITER).

   (c) third, new approaches for fueling, e.g., based on Morozov rings, could be developed if conventionql ones does not work.

2. Q. What about chemical retention of D,T in Li ?

   A. *So far, based on T-11M and PISCES data, there is no concern related to chemical retention of the D,T in Li. D is released when the temperarature of Li exceeds 400^o C*

3. Q. Helium exhaust was a reason of abandoning the wall based fusion ?

   A. *Helium ash should be retained in the streams for 1/4 sec. Mixing only 0.1 mm of the surface layer with the bulk of Li would be sufficient. Any MHD oscillations and noise, inavoidable in the high-β plasma will help in mixing.*

4. Q. Why the plasma between terminals of Lithium Streams does not make a short circuit ?

   A. *In a reactor, which, e.g., consumes 1 g/sec of DT fuel, the ion current is limited by 0.1 MA. Only a portion of it can participate in the short circuiting. For comparison, the current required for Intense Lithium Streams is about 1.5 MA.*

5. Q. What is the most appropriate plasma shape for the LiWalls ?

   A. *Circular cross-section tokamaks are the most appropriate. The non-circular (D-shaped) cross-section deteriorates the centrifugal stabilization of the streams. It also makes alignment of the plasma boundary and the wall surface more diffcult.*

6. Q. Are stellarators compatible with the LiWalls ?

   A. *Intense Lithium Streams, the basic element of the LiWall fusion reactor, are not possible in stellarators.*

7. Q. Can diagnostic ports be made in the Li walls ?

   A. *For both solid LiWalls and for Intense Lithium Streams the diagnostic ports can be designed. Some loss of power extraction capability is expected.*

8. Q. Can ILS withstand the disruption ?

   A. *Electromagnetically yes. Probably, they also can withstand the sudden power deposition (T-11M data on self-protection)*

9. Q. How essential can be the Kelvin-Helmholtz instability ?

   A. *Not for entity of the streams. It is useful for the power and Helium extraction.*

10. Q. Is the Li supply possible from outside the tokamak ?

    A. *High speed (20-40 m/sec) jets with a sub-centimeter diameter are able to penetrate into the strong magnetic field. Such jets inside a pressurized pipe can be used for Li supply to inlet of the streams.*

11. Q. Is the Li ejection possible to outside the tokamak ?

    A. *At the outlet the Li flow should be converted into the shower of jets. Certain level (not yet determined) of the electromagnetic pressure can convert the flow into jets. Then, they can fly out of the magnetic field of the tokamak.*

12. Q. Does the flowing lithium required ?

    A. *Not at all for the experimental research studies up to demonstration ignition. At this stage, the flowing lithium serves against LiWalls. Li coating, Li pellet injection, of DOLLOP is much more appropriate. The flowing lithium is neaded only for the power reactor.*

13. Q. What is the smallest appropriate tokamak for LiWalls ?

    A. *To my knowledge, in the US, this is the TEXT tokamak. It should have additional (electron) heating, pellet injection, and the circular cross-section.*